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Life-Cycle Cost Analysis of Pavement Preservation Techniques in Texas

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Life-Cycle Cost Analysis of Pavement Preservation Techniques in Texas

by

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Thesis

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To my loving parents, Elia Mercedes and Wilfrido.

To my siblings, Eduardo and Elia María, with whom I have shared it all.

To my grandfather. I miss you dearly.

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Abstract

Life-Cycle Cost Analysis of Pavement Preservation Techniques in Texas

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The proper implementation of pavement preservation techniques can extend the life of a pavement structure in a cost-effective manner. For this reason, a large part of the Texas Department of Transportation (TxDOT) annual budget is assigned to the maintenance and rehabilitation of the State highway network. Within this budget, a fair share is allocated to the implementation of preventive maintenance (PM) techniques, whose timely application has proved the best approach to keep the pavement sections in "Good" or "Very Good" condition. The main objective of this research study was to develop a probabilistic life-cycle cost analysis (LCCA) that allowed the evaluation and comparison of highway pavement sections subjected to one of the three main PM treatments used in Texas, namely, chip seals, microsurfacing and thin overlays. Effective life and the cost per mile lane were the main variables used to develop the analysis.

The analysis was performed through Monte Carlo Simulation using data from TxDOT databases containing historical information on more than 14,000

projects constructed between 1994 and 2016. Because TxDOT maintains a plethora of information on its databases, the methodology to use those databases and to extract the relevant information used in this study was also described. During the study, the effect of the facility type, traffic volume and traffic loads on the treatments were also analyzed.

Based on the results of the analysis, it was established that all three treatments present a similar service life regardless of external factors, but have different costs, with chip seals having the lowest, followed by microsurfacing and thin overlays. Findings suggest that chip seals have the most cost-effective LCC, even in environments where they are not commonly employed, like heavily trafficked sections. However, microsurfacing emerges as an interesting alternative as traffic volumes and traffic loads increase. Finally, thin overlays are to be evaluated in a case-by-case basis as they have the less predictable behavior. This is most probably consequence of being the newest type of treatment, having the steepest learning curve. They could work well in pavement sections located in intersections, turning points and stop signs, where higher shear stresses are involved.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Motivation

Roads are ubiquitous in everyday life, and are a critical infrastructure asset for governments and citizens alike. The American Society of Civil Engineers (ASCE) has rated the current condition of roads in the United States with a D+ (at risk), placing in the lowest possible tier (ASCE, 2013). The Federal Highway Administration (FHWA) estimates $170 billion dollars would be needed on an annual basis to improve the conditions and performance of existing roads (ASCE, 2013) to a "Good" condition level. The Fiscal Size-Up 2016-2017, produced biennially by the Legislative Budget Board of Texas, says $23.1 billion dollars in the State All Funds Budget are provided biannually for all functions of the Texas Department of Transportation (TxDOT). $19.7 billion are assigned for transportation planning and design, right-of-way acquisition, construction, and maintenance and preservation. This amount includes $8.8 billion for maintenance and preservation of the existing transportation systems, and $5.8 billion for construction and highway improvements.

A large share of the total budget is directed towards the maintenance, preservation and enhancement of the condition of the roads in Texas. These efforts include the implementation of pavement preservation techniques, which are applied to extend the service life of pavement sections, and increase their structural capacity in some cases. The performance of a pavement structure throughout its service life is affected by several factors that are uncertain due to their inherent variability or poor quality control, such as traffic, weather, and material properties (Serigos, 2016). Preventive maintenance (PM) treatments can serve as a cost-effective strategy to maintain the functionality level of pavements with minor distresses (Buddhavarapu, 2011).

Empirical evidence showed timely maintenance to be the best approach to delay the deterioration rate of a given pavement surface, effectively extending its service life at the lower possible cost. TxDOT generally uses one of three PM treatments: chip seal, also known as seal coat, microsurfacing and thin overlay. Their main function is to counter pavement deterioration, but these treatments have also been used to improve ride quality, correct minor distresses, improve safety characteristics, enhance appearance, and reduce road-tire noise (Buddhavarapu, 2011).

It has been suggested PM treatments are placed on a four-to-20-year cycle (Wu et al. 2010). This is not always possible due to funding constraints and difference in the deterioration rates for PM treatments. More often than not the decision to implement them depends solely on the judgement of maintenance section supervisors and area engineers (TxDOT, 2017). The process for selecting which pavements are to receive PM treatment, when they receive it, and the type of treatment they receive, varies across districts. Chip seals have been the traditional PM treatment of choice. However, the development and good performance of microsurfacing and, more recently, thin overlay suggests they may not always be the best alternative. Different influence factors, such as, location within the road (e.g. intersections, stop signs, slopes, curves), type of traffic (e.g. percentage of trucks, congestion trends, urban and non-urban areas), geographic conditions (e.g. precipitation, temperature), and subgrade materials (e.g. clay and non-clay) should be accounted for.

Despite the improvements in data collection for estimating the service life of maintenance and rehabilitation (M&R) practices, these data have not been extensively used (Jeong and Pour, 2012). Additionally, there is a lack of a standard methodology to objectively quantify the benefits of applying light rehabilitation work, preventative maintenance or routine maintenance, given that different districts and states have approaches that differ vastly between themselves. TxDOT operates a statewide information system that allows all districts and Austin headquarters to maintain project data in a common format. These data are stored into a number of automated information systems and databases. They include, among other factors, information on the design, construction, cost, traffic operation, location, construction and replacement date, and roadbed type of the different projects in Texas.

Unlike the traditional "Worst First" pavement maintenance programs, pavement preservation is a proactive approach to treating pavements before they fall into despair (Geiger, 2005). Preservation keeps roads in a good condition (Galehouse et al., 2003). Therefore, calculating the benefits resulting from pavement preservation is important for state transportation agencies (Gransberg et al., 2010). It was reported that timely pavement preservation is cost-effective because rehabilitation costs increase exponentially with the degree of deterioration (Yapp, 2009). Neglecting preventive maintenance can lead to structural deterioration requiring major rehabilitation or even full reconstruction. This becomes even more crucial if we consider that the information needed is readily available. The most popular tool to quantify the economic benefit obtained from the implementation of PM treatments is the Life-Cycle Cost Analysis (LCCA). LCCA builds on the well-founded principles of economic analysis to evaluate the over-all long-term economic efficiency between competing alternatives (Walls and Smith, 1998). By implementing LCCA, the heterogeneity in the service life and cost of the PM treatments can be taken into consideration. This is done by associating PM treatments with a range of values obtained from the population distribution, and accounting for existing variability in the data.

This research work aimed at developing a probabilistic LCCA framework to evaluate and compare highway pavement sections subjected to pavement different preventive maintenance treatments. For this study data collected by TxDOT was utilized in order to highlight the economic benefit that the timely use of PM treatments can bring by extending the life of a pavement sections in an efficient and sustainable way.

Objectives

The focus of this research was to conduct LCCAs for the three most popular PM treatments used in Texas (chip seals, microsurfacing and thin overlays), accounting for their distribution. The distribution associated with each of these variables was estimated using data collected over 20+ years by TxDOT. The FHWA approach to LCCA (FHWA, 2002) was used as a base for conducting the LCCAs.

The three main objectives were:

1. To develop a probabilistic life-cycle cost analysis that allowed for the evaluation of the three preventive maintenance treatments most commonly used in Texas – chip seals, microsurfacing and thin overlays – by comparing their economic benefits.
2. To investigate the effect that facility type, traffic volume and traffic loads had on the effective life and cost of the preventive maintenance treatments, and
3. To develop a methodology to extract, refine and make use of the information contained in TxDOT-maintained databases, so that the experiment can be repeated.

Scope and Methodology

Many theoretical methods have been developed to score the condition of both flexible and rigid pavements. This thesis considered flexible pavements as they were the ones receiving the analyzed types of PM treatments. There is no consensus on what method is better to determine the overall condition of the highway pavement. Texas uses three different scores, but in practice TxDOT does not rely only on the obtained score. Rather, it follows a four-year plan to determine the condition of its managed roads and determine whether M&R action is needed – and if so – to what extent. This work sought to evaluate and compare three PM treatments most commonly used by TxDOT, to incorporate knowledge about their cost-effectiveness into the decision process, making it more robust. LCCAs were run for different conditions to gain insight on the conditions affecting the performance of PM treatments.

PM is not the only M&R option, but experience and research determined it to be more cost-effective than major rehabilitation (i.e. light, medium, heavy). Thus, the focus to study PM treatments was because it is, and has been, the most widely M&R action employed by TxDOT. PM has been used six more times than medium rehabilitation, and eleven more than heavy rehabilitation in recent years, as seen in Figure 1. This study included data collected between 1994 and 2015. The used data was not stored in a single information system or database. Compiling a final database was not straightforward. Information was extracted from several databases and reformatted for consistency. The particularities of each of the included TxDOT databases were described as well as the steps followed to conform a database that suited the needs of this work based on the available information.

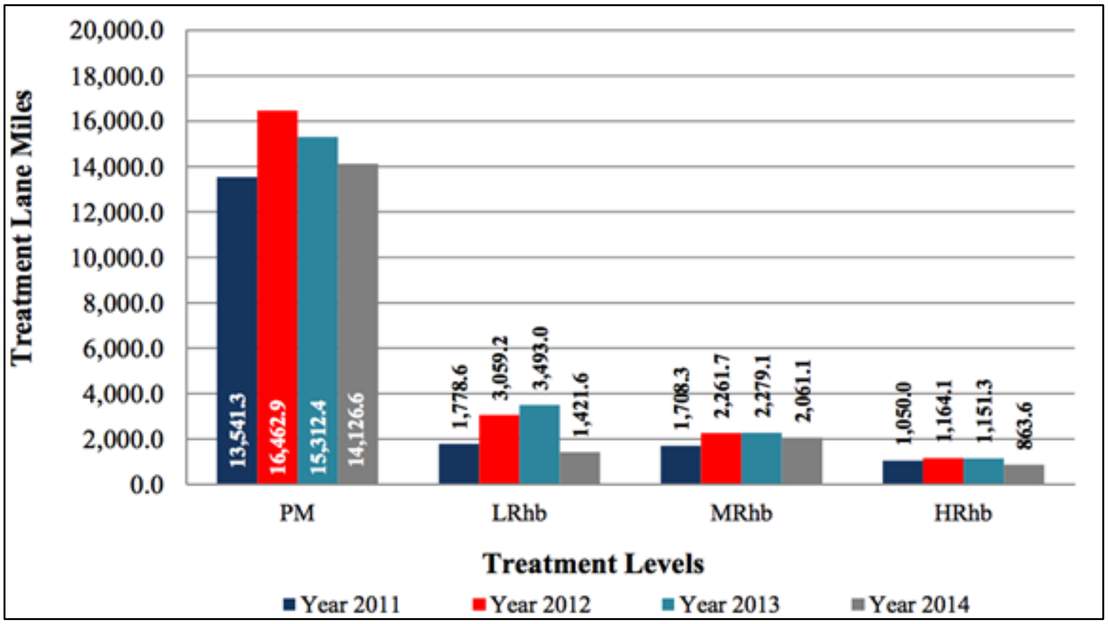

Figure 1: Statewide M&R Plans for FY 2011-2014 (Source: Jaipuria, 2011)

In this study it was assumed that the treated pavement sections were still in a "Good" condition and structurally sound (i.e. not in need of major rehabilitation). Only PMs applied to flexible pavements were considered. An important assumption was that once a PM treatment was implemented in a given section, the same type of treatment was going to be applied throughout time, as in common practice (Wimsatt et al., 2005).

The developed LCCA was adapted from the FHWA methodology (FHWA, 2002). The random variables considered in the LCCA were the effective life and the cost of the treatments. The simulation for the study used a probabilistic approach as it was deemed it would yield more realistic and valuable results than a deterministic one. The probabilistic approach allows the use of the entire distribution to characterize each of the variables as opposed to the deterministic LCCA. The later needs single-value inputs (usually the mean of the distribution), and fails to acknowledge possible variability in the data. Distributions that could potentially fit the effective life and the cost were explored. The simulations were run employing Monte Carlo Simulation (MCS) via MATLAB. The study was set in a 25-year window of analysis, and it was assumed the first PM treatment for every studied case was applied at the same time. To allow for a fair comparison of the results, all results were converted to dollars per lane mile, in 2017 dollars.

To study the effect traffic had on the performance of the treatments, a sensitivity analysis was performed with the different traffic categories and the PM treatment type. The traffic factors included were annual average daily traffic (AADT), equivalent single axle load (ESAL) and highway designation. The results are presented, and possible causes leading to them discussed. It is important to remark that field implementation of the guidelines with control sections is necessary for the validation of the results, however, implementation was beyond the scope of this work.

Description of Contents

This thesis consists of six chapters: Introduction; Literature Review; Information Gathering and Breakdown; Methodology; Life-Cycle Cost Analysis Results; and, Conclusions and Recommendations.

In this chapter, the research problem, motivation, objectives, scope and methodology are presented. Chapter 2 provides a comprehensive review of the methods used to determine the selection of maintenance and rehabilitation (M&R) activities in TxDOT-maintained roads based on different methods to assess the condition of the pavement sections. The TxDOT four-year plan is discussed, and the available M&R strategies are described. This section also presents previous research that employed LCCA to analyze the use of PM treatments. It contains the definition of Life-Cycle Cost, and explains the difference between deterministic and probabilistic LCCAs. A justification for using the latter is provided. Finally, it describes the general steps of the LCCA procedure, and the modifications it underwent to fit the purposes of this work.

The first part of Chapter 3 describes TxDOT´s databases and the information they contain. TxDOT-maintained databases used to extract the information for this study are described; the concept of "effective life" is introduced and probability distributions that could fit the data are described. Afterwards, the concept of cost for this thesis is defined followed by a description of the different factors that have an effect (and are comprised) in the costs of applying PM treatments. Additionally, this chapter provides a description of probability distributions that could accommodate the distribution of the cost of the PM treatments included. Traffic information indicators are explained. Finally, the environmental factors that affect the performance of pavements are presented.

Chapter 4 presents the methodology followed to extract the information to run the LCCA. This information was stored on TxDOT databases, and the factors relevant for the study are explained. Then, the life-cycle cost analysis developed for this work is explained step-by-step, laying out the assumptions that were considered. Chapter 5 focuses on the life-cycle cost analysis per se, presenting the results obtained using the information extracted from TxDOT databases, and providing insight on the obtained results, as well as exploring some of the factors that could have a large effect on the cost and performance of the studied PM treatments. In Chapter 6, Conclusions and Recommendations from the study are presented, followed by a discussion of ideas for future work.

Chapter 2: Literature Review

Pavement Preservation

TxDOT´s Pavement Design Guide states a flexible pavement structure is typically composed of several layers of material. Better quality materials are on top – where the intensity of stress from traffic loads is high – and lower quality materials at the bottom – where the stress intensity is lower. Flexible pavement structures under traffic loading can be analyzed as a multilayer system. A typical flexible pavement structure consists of the surface course and underlying base and sub-base courses. Each of these layers contributes both to structural support and to drainage. When hot mix asphalt (HMA) is used as the base course it is the stiffest layer (as measured by resilient modulus) and may contribute the most – depending upon thickness – to pavement strength. The underlying layers are usually less stiff but are still important to pavement strength as well as drainage and frost protection (TxDOT, 2011). The function of the HMA layer is to prevent the layers below to be affected by traffic loads and environmental conditions, like precipitation infiltration. The surface layer should also provide functional benefits in terms of friction, reduced rolling resistance, reduced noise, etc.

The primary structural difference between a rigid and a flexible pavement is how each type of pavement distributes traffic loads over the subgrade (TxDOT, 2011). In a rigid concrete pavement, the surface slab has a very high stiffness and distributes loads over a relatively wide area of subgrade – the slab itself contributes with a major portion of the structural capacity. On the other hand, the load carrying capacity of a flexible pavement is derived from the load-distributing characteristics of a layered system (TxDOT, 2011), as seen in Figure 2. In general, flexible pavement surfaces deteriorate faster than rigid pavement ones. Depending on the design, construction procedures, and conditions of service it is expected asphalt concrete (AC) pavements are going to deteriorate over time, and pavement preservation is necessary to manage and delay this process. From now on, in this work "pavement" will refer exclusively to flexible pavements, unless otherwise stated.

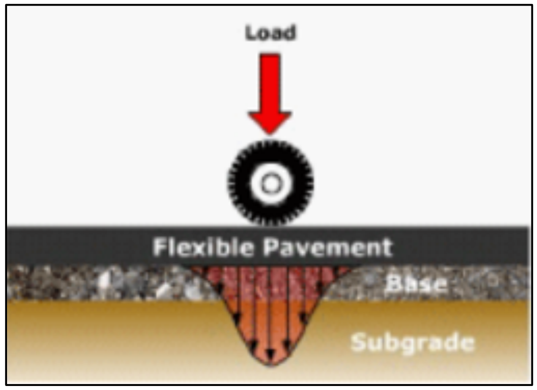

Figure 2: Stress Distribution under Flexible Pavement (Source: TxDOT, 2011)

The FHWA defines pavement preservation as a program employing a network level, long-term strategy, looking to enhance the condition of the pavement network by implementing an integrated and cost-effective set of practices that extend the life of a pavement, improve safety and meet motorist expectations. Pavement preservation practices comprise three main components, depending on the stage – or time – at which the pavement is studied: i) light or non-structural rehabilitation, ii) preventative maintenance and iii) routine maintenance (Geiger, 2005), as seen in Figure 3. The figure shows that serviceability of a pavement structure is going to decrease over time. To slown down or delay the drop in the serviceability curve and maintain the pavement in a "good" condition, it is necessary to apply routine maintenance. However, routine maintenance cannot be applied indefinitely. At some point in time, the pavement is going to need preventive maintenance – which is the stage that this work addresses – to maintain the pavement in a "good" condition. Finally, the pavement will reach a serviceability level where rehabilitation is needed. If any of these three components is neglected, the serviceability of the pavement is going to decrease faster than if they are implemented.

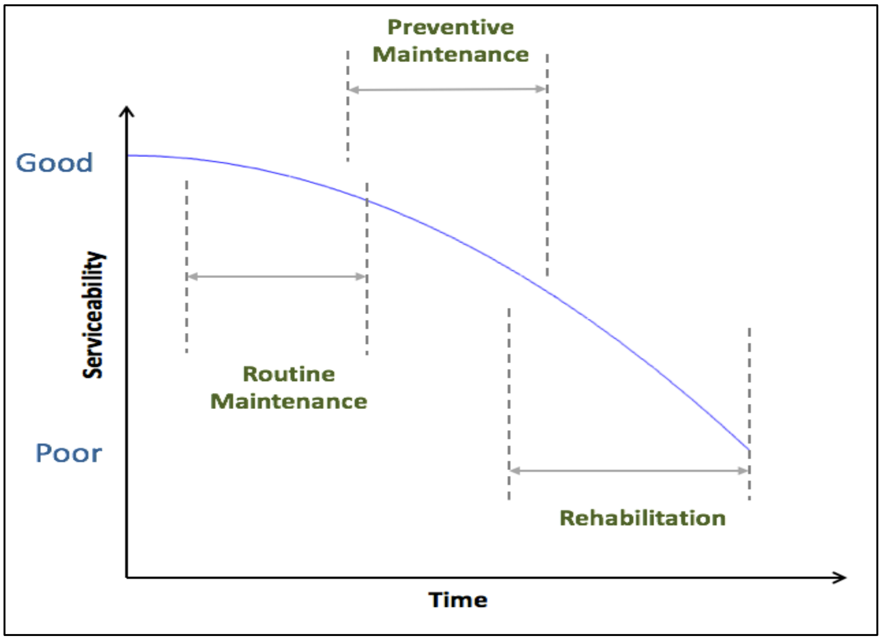

Figure 3: Pavement Preservation Treatments (Based on: Chang, 2014 and Serigos, 2016)

Light rehabilitation consists of non-structural enhancements made to the existing pavement sections to eliminate age-related, top-down surface cracking that develop in flexible pavements due to environmental exposure (FHWA, 2005). The preventive maintenance process is the systematic application of a series of maintenance actions over the service life of a pavement, targeted to maintain a good condition, extend its lifespan, and minimize the life-cycle cost (LCC) through the use of analysis techniques (Peshkin et al., 2004). Finally, routine maintenance can be defined as work planned and performed on a routine basis to maintain and preserve the condition of the system, or to respond to specific conditions and events that restore said system to an adequate level of service (Pavement Interactive, 2013).

The application of PM treatments is a critical part of the pavement preservation program as implementing them decrease the rate of pavement deterioration to meet performance standards. These treatments are also used to maintain an acceptable surface friction on the pavement and prevent water from infiltrating through the pavement and reaching the subgrade. PM treatments are applied while the roadway is still in a good condition and shows only minimal distresses, before the pavement falls into a condition where placing structural overlays, major milling or reclaiming, or replacement is necessary (Chang et al., 2008).

Pavement Condition Assessment

Numerous score names and rating methods have been developed by state transportation agencies across the country to assess the condition of a pavement, and there appears to be little consistency among them (Papagiannakis et al., 2009). These scores can be used at times for recommending pavement maintenance and rehabilitation actions. The contrast between methodologies is noticeable in that they consider different attributes (i.e. extent, severity and/or type of distresses), and do not have uniform scales (i.e. continuous or discrete) nor uniform scale descriptions. This means that what can be considered a good condition in Texas could be different to what is considered good in other states. In turn, this affects the recommended M&R actions. M&R decisions could be quite different even in cases where the conditions of two pavement sections are similar. Further, state agencies define different lengths in their evaluated sections (e.g. 0.04 miles in Montana, two to three miles in Ohio, and an undefined length in more than half the states) as well as different survey frequencies (e.g. annually in 24 states, and biennially or undefined in the rest).

TxDOT uses both extent and type of distress as attributes, with severity level only used for rut depth and ride quality assessment. As mentioned before, PM treatments can only be applied when the pavement is still in a good condition and does not need structural reinforcement. Pavements in Texas are evaluated every half-mile on an annual basis. For this, TxDOT employs different continuous-score methods to indicate pavement condition: ride score (RS), distress score (DS), and condition score (CS). Some districts, such as the Austin district, use other scores like the structural condition index (SCI) (Pappagiannakis et al., 2009). As a consequence, there is more than one theoretical methodology and criteria that can be selected to discriminate between pavements that are still in a good condition and those that are not. For TxDOT, the pavement condition depends on the combination of distress and ride scores, which, as mentioned before, may not be the case for other states.

DISTRESS/CONDITION SCORE

TxDOT interprets distress for AC pavements as cracking, rutting, patching and faliures, and does not include ride. Rutting and cracking are divided into different types. Distress scores (DSs) for each type of distress are combined to determine the overall DS. The types of surface condition data collected by TxDOT are defined in the PMIS Raters Manual protocols (TxDOT, 2015), and include eight distress types for AC surfaces – shallow rutting, deep rutting, patching, failures, alligator cracking, block cracking, longitudinal cracking and transverse cracking – five for CRCPs, and six for jointed concrete pavements (JCPs) (Goehl, 2013). TxDOT currently uses visual inspection by raters as well as automated distress measurements (since FY2017) for all distresses except rutting, which is measured using TxDOT's rut bar attached to the profile (Serigos, 2012). Each surface condition is used to calculate a utility value (Serigos, 2016), with the basic shape of a pavement's utility curve being sigmoidal, or S-shaped (Stampley at al., 1995). Each surface condition is thus used to calculate a utility value ranging from zero to one, which may be expressed as:

$$\mathrm{Ui} = 1 - \alpha \mathrm{e}^{-\left(\frac{\rho}{\mathrm{Li}}\right)^{\beta}} \tag{2.1}$$

Where:

Ui – utility value for PMIS distress type i

α – horizontal asymptote factor that controls the maximum amount of utility that can be lost

β – slope factor that controls how steeply utility is lost in the middle of the curve

ρ – prolongation factor that controls "how long" the utility curve will "last" above a certain value

Li – percentage of the level of distress or ride quality loss for surface condition

Factors α, β and ρ are computed as a function of the type of pavement type for the distress utility type for the distress utility curves (Stampley at al., 1995). Having utility curves for the different distresses allows the system to account for the actual impact they have on the overall condition of the pavement. For example, as seen in Figure 4, for AC pavements, transverse cracking has a greater impact on the overall condition of a pavement than longitudinal cracking does. The lower the quality value, the higher the impact

(Serigos, 2016). The impact assigned to each distress measurement was defined by TxDOT based on engineering judgement (Serigos, 2016). Once the eight utility scores have been obtained, the DS to define the overall level of damage in the analyzed pavement can be calculated as a function of the utility values, as expressed in Equation 2.2.

$$\mathrm{DS} = 100 \prod_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Ui} \tag{2.2}$$

Where:

DS – distress score

Ui – utility value for distress i

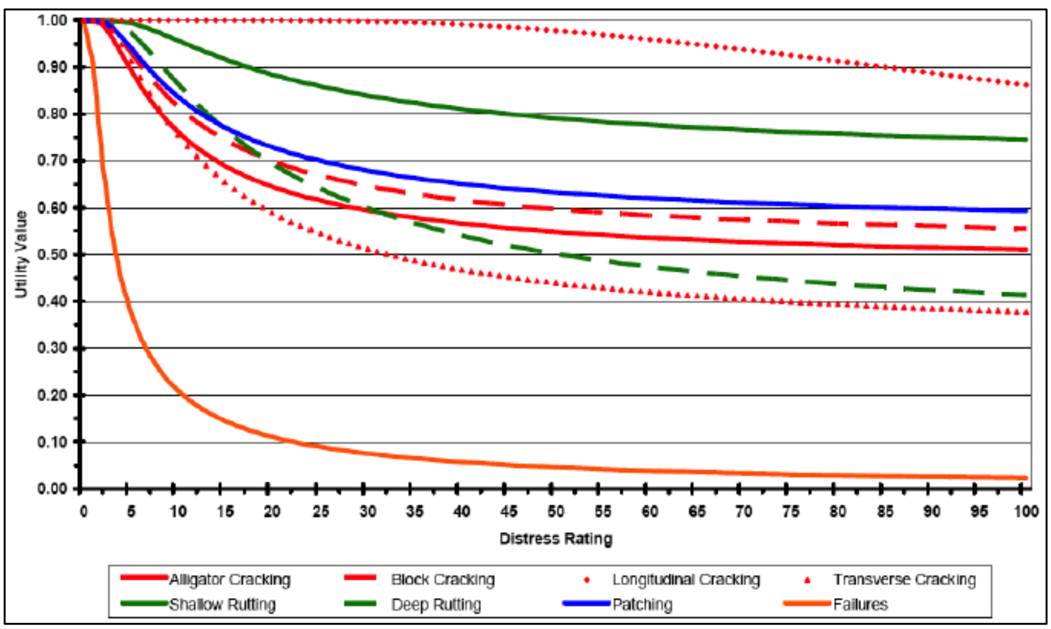

Figure 4: AC Pavement Distress Utility Values (Source: Goehl, 2013)

Because the CS to describe the theoretical overall condition of the studied pavement surface depends on both the DS and RS, the RS needs to be obtained next. The RS is determined by converting the actual roughness (in IRI) measured in the field. The Ride Score converts IRI into a zero to five scale. Then the ride quality score utility (U_r) can simply be obtained through the ride quality utility curves as seen in Figure 5, which are function of the pavement type and the traffic level. The condition score is then calculated using Equation 2.3.

$$CS = DS \cdot U_r \tag{2.3}$$

Where:

CS – condition score

DS – distress score

U_r – ride quality score utility

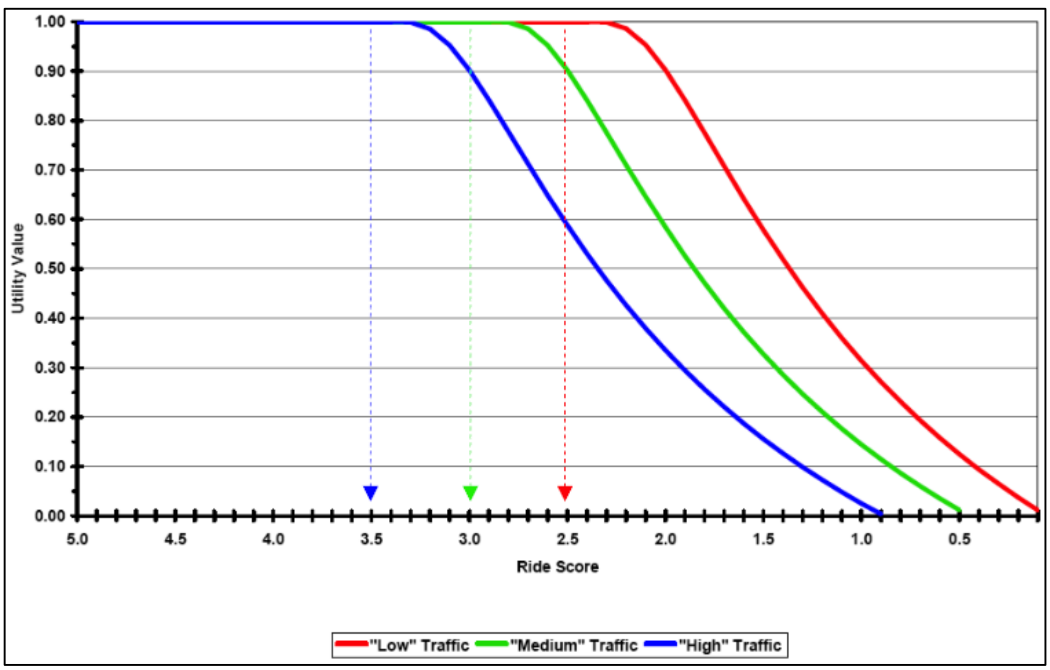

Figure 5: Ride Quality Utility Values for Flexible Pavements (Source: Goehl, 2013)

Following TxDOT guidelines, the condition of a given pavement section could be obtained based on Table 1.

Table 1: PMIS Score Definitions (Source: TxDOT, 2014)

Distress Score	Ride Quality Score	Condition Score	Condition
90–100	4.0–5.0	90–100	Very Good
80–89	3.0–3.9	70–89	Good
70–79	2.0–2.9	50–69	Fair
60–69	1.0–1.9	35–49	Poor
1–59	0.1–0.9	1–34	Very Poor

INTERNATIONAL ROUGHNESS INDEX

IRI has been implemented worldwide to compare pavement smoothness, and IRI has the advantage that measures from different states are largely compatible (Sayers and Kamihas, 1998). Typical IRI Scores for different conditions of usage are shown in Figure 6. The IRI was first recommended as a standard for roughness measurements at the International Road Roughness Experiment in 1982, after the California Profilograph and the Profile Index were deemed not accurate enough (MnDOT, 2007). Their main disadvantage was that it was not possible to obtain the same values from different vehicles, or even from the same vehicle over time (Sayers and Kamihas, 1998).

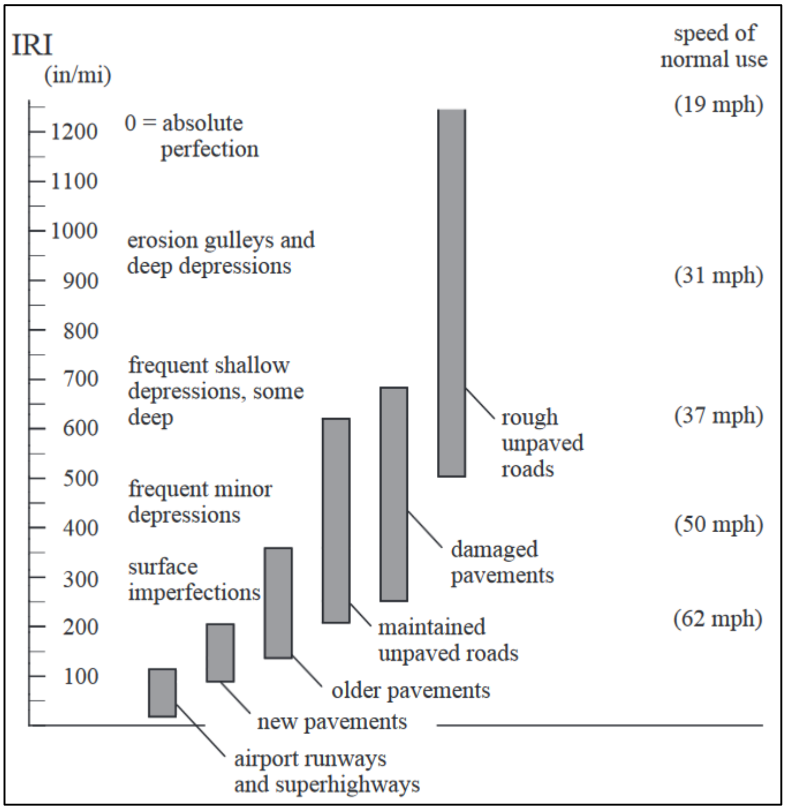

Figure 6: IRI Scores for Different Pavement Usages (Source: Sayers and Karamihas, 1998)

IRI can be understood as a scale for roughness based on the simulated response of a generic motor vehicle to roughness in a single wheel path of the road surface (MnDOT, 2007). However, rigorously speaking IRI is defined as a specific mathematical transform of a true profile (Sayers and Kamihas, 1998). Sayers and Kamihas describe the procedure to obtain the IRI Score in the Little Book of Profiling (1998). To calculate it, first a profiler measures the longitudinal road. Then, the profile is filtered with a moving average with a 250-millimeter base length, effectively smoothing the profile. In other words, this filter lowers the sensitivity of the IRI algorithm to simulate the effect of the tire (Prozzi et al., 2017a). This filtering should be omitted if the profile has already been filtered.

The profile is further filtered with a quarter-car simulation, whose parameters are specified as part of the IRI statistic, and the simulated travel speed specified as 50 mph. This filter is employed to calculate the suspension deflection (Prozzi et al., 2017a). The imaginary quarter car is mathematically represented with a vertical spring, the mass of the axle supported by the tire, a suspension spring and damper, and the mass of the body supported by the suspension for that tire (Prozzi et al., 2017a). Thus, the output of the filter represents the suspension motion of the simulated quarter car.

Afterwards, the filtered profile is accumulated by adding absolute values and then is divided by the profile length. IRI is normally reported in inches per mile, meter per kilometer or milimeters per meter. In principle, IRI values range from 1 (smoothest) to approximately 950 (roughest), and allow to define – in theory – the condition of the pavement as seen in Table 2. It is important to remark that these IRI categories are not the same as the Ride Score categories shown in Table 2 (e.g. "very good" Ride Score is not analogous to "very good" IRI Score). This means Ride Score and IRI will not yield the same results, but they will show the same trends over time (TxDOT, 2008).

Table 2: IRI Scores Definition (Source: TxDOT, 2008)

IRI Score	**Condition**
1–59	Very Good
60–95	Good
96–130	Fair
131–169	Poor
170–950	Very Poor

The length of the test segment has a strong influence on the obtained IRI values. The IRI calculated for a long segment shows overall ride condition of a pavement, diminishing the effect of localized roughness. On the other hand, IRI values in short segments underscore the effect of localized roughness (Prozzi et al., 2017a). This phenomenon is statistically known as the regression to the mean. For this, a project length of at least 196.8 feet is required to measure IRI. The IRI is defined by a mathematical function of the longitudinal profile rather than by a piece of equipment, making it time stable. Further, the FHWA has required states to measure IRI on the National Highway System since 1993 because the results are reported to Congress to inform its budget distribution (MnDOT, 2007).

STRUCTURAL CONDITION INDEX

The decision to implement or not PM treatments could also be explored theoretically from the structural point of view (TxDOT, 2014). Zhang et al. (2003) found that the use of the Structural Condition Index (SCI) has proven to be effective in differentiating pavements that need structural reinforcement from those that are in sound structural condition. This index is particularly suitable for pavements in Texas since it was developed based on TxDOT data from the Pavement Management Information System (PMIS) using the falling weight deflectometer (FWD) test.

First, the deflection of the pavement structure is computed as follows:

$$\mathrm{SIP} = \mathrm{D}_0 - \mathrm{D}_{1.5\mathrm{Hp}} \tag{2.4}$$

Where:

SIP – structural index of pavement (μm)

D_0 – peak deflection measured under standard 9,000-lb FWD load (μm)

$D_{1.5Hp}$ – surface deflection measured at offset of 1.5 times of Hp under standard 9,000-lb FWD load (μm)

Hp – total pavement thickness

Once the SIP value has been obtained, it is possible to estimate the structural number of the pavement with the known total thickness of the pavement, with the following function:

$$SN = k1 \cdot SIP^{k2} \cdot Hp^{k3} \tag{2.5}$$

Where:

SN – pavement structural number (in)

SIP – structural index of pavement (μm)

Hp – total pavement thickness (mm)

k1, k2, k3 – regression coefficients (as given in Table 3)

Table 3: Coefficients for SN versus SIP Relationships (Source: Rohde, 1994)

Surface Type	**k1**	**k2**	**k3**	**r^2***	**n****
Surface Seals	0.1165	-0.3248	0.8241	0.984	1944
Asphalt Concrete	0.4728	-0.4810	0.7581	0.9570	5832

*Coefficient of Determination

**Sample Size

Since the SN estimates are sensitive to the pavement deterioration variables, their values can be used as a good indicator if the existing structural condition of a pavement (Zhang et al., 2003). Once the SN values have been obtained, the SCI can be established, expressing it as the ratio of the existing SN and the required SN, as in Equation 2.6.

$$SCI = \frac{SN_{eff}}{SN_{req}} \quad (2.6)$$

Where:

SCI – structural condition index

SN_{eff} – existing structural number (in)

SN_{req} – required structural number (in)

The interpretation of the SCI is straightforward. If it is equal or greater than one, the pavement is structurally sound. On the contrary, if it is smaller than one it could indicate that the pavement is no longer structurally sound, and rehabilitation work that may enhance its structural capacity should be considered. TxDOT does provide guidelines on the recommended actions to take based on the SCI Score of a pavement, presented in Table 4.

Table 4: Structural Condition Index Threshold Values (TxDOT, 2014)

SCI Scores (SCI*100)	Condition	Treatment Level
90–100	Very Good	Do Nothing
80–89	Good	PM Treatment
65–79	Fair	Light Rehabilitation
50–64	Poor	Medium Rehabilitation
0–49	Very Poor	Heavy Rehabilitation

FOUR–YEAR PLAN

Although any of the three methods described above could be selected to theoretically assess the condition of pavements in Texas and decide whether a given section needs the implementation of pavement preservation treatments, TxDOT has designed a strategy to enhance the decision-making process and keep a consistent standard across the state. Thus, the decision depends not only on the condition of the pavement, but also takes into consideration factors like budget constraints, traffic volumes, district policy and engineering judgement.

The so-called Four-Year Pavement Management Plan Development (commonly known as the "four-year plan"), was developed based on the premise that TxDOT is required to provide the Legislative Budget Board and the Governor with a detailed plan for the use of the funds it receives (Zhang and Murphy, 2012). This is because pavement needs always exceed the available pavement maintenance funding. This plan should include – but is not limited to – a district-by-district analysis of pavement score targets and describing how proposed maintenance spending will influence pavement scores in each district. To fulfill this requirement, TxDOT and its districts apply the four-year pavement management plan (updated every year) to predict the future conditions of the pavements and establish a route of action.

For this, the four-year plan provides each district with a list of pavement projects that have been identified for maintenance or rehabilitation in the current and three future fiscal years (Zhang and Murphy, 2012). To maximize the use of limited expenditure resources, the plan is updated annually by the districts in a process that involves three steps: network-level project screening, project-level ranking process and economic analysis.

- Network-Level Project Screening – Candidate projects are identified using PMIS data and various data analyses, mapping, and reporting tools. A list of prioritized, candidate projects is identified by the district pavement engineer, area engineers, and maintenance supervisors – based on the PMIS databases, field visits to candidate project sites, and additional information about local conditions (e.g. safety investigations, impact of heavy truck operations). The candidate list of projects is then revised and prioritized by the district engineer and his management team, with the district coordinating with metropolitan planning organizations (MPOs), counties and cities. Projects are then programmed and assigned to either the current or a future year, depending on safety issues and crash history, traffic volumes, anticipated pavement preservation rates, available funding, and district/statewide condition score goals.

- Project-Level Ranking Process – Projects in the early years of the plan are selected for detailed project-level field investigation and testing. TxDOT non-destructive testing includes FWD, ground-penetrating radar, pavement coring, among others, obtained to determine the causes of distresses. This information is also used to help identify treatment strategies (i.e. preventive maintenance, light, medium or heavy rehabilitation). The project-level investigation also helps determining if a section can be delayed or requires immediate attention.
- Economic Analysis – A benefit/cost analysis is performed to determine the relationship between treating selected projects and the increased costs and loss of condition should a project be delayed.

PAVEMENT CONDITION PREDICTION MODEL

To determine more accurately the moment when a pavement needs M&R action, deterioration models that predicts the deterioration of pavements based on several factors such as climatic region, historical deterioration, and highway type have been developed (Jaipuria et al. 2011). The model is loaded with the four-year plan proposed improvements and the deterioration rate that is expected from a given section. This model then yields predicted pavement condition scores, which are used to determine the priority of the different sections, considering that the Texas Transportation Commission has set as a goal that 90 percent of the pavements have to be rated "Good" or better at any given point in time.

Because PM treatments are in general more cost-effective than light, medium, and heavy rehabilitation, the model seeks to take action on the pavements before they are beyond the point where PM treatments suffice and major rehabilitation is required. This results in a variable pavement maintenance spending, that depends on the percentage of roads that are in a "Good" or better condition in a given year, as seen in Figure 7. As observed in the figure, at least an 86 percent of the lane miles have scored "good" or better, but it has fallen short of the 90 percent objective in every year. It can also be seen that the condition and spending are not linearly related, therefore, when and what kind of M&R is applied weights more than how much money is spent to achieve the goal.

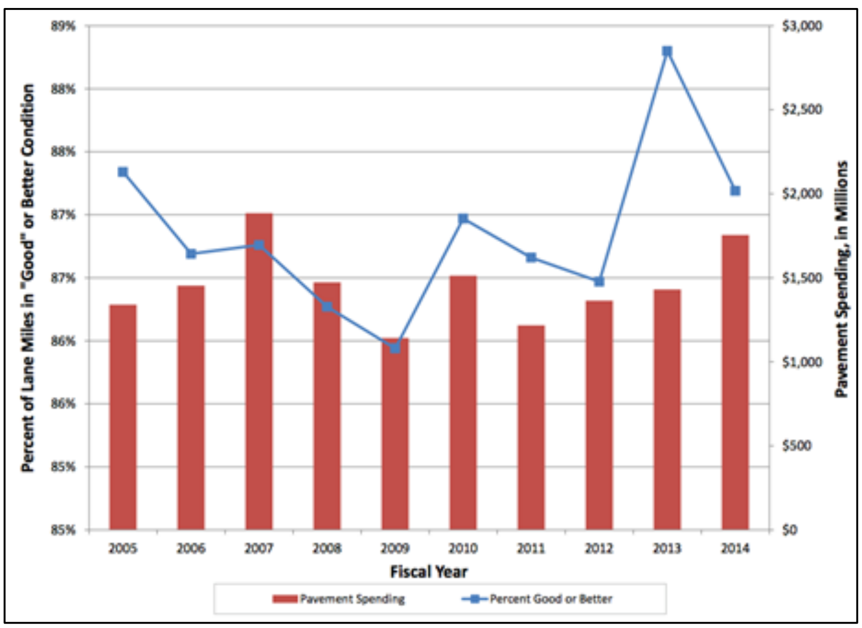

Figure 7: Statewide Percentage of "Good" or Better and Maintenance Expenditure FY 2005-2014 (Source: TxDOT, 2014).

M&R Strategies

Once a means to describe or score the condition of a pavement has been selected, and it has been defined as a pavement section being in a state where M&R is required, a PM treatment or rehabilitation type ought to be selected. It has been established that the application of a PM treatment is necessary to maintain good operational conditions and prevent the need of future rehabilitation (either light, medium or heavy). However, this depends on both the stage when the M&R is applied, as well as the condition of the pavement. As seen before, timely application of M&R is considered the most cost-effective strategy, with PM treatments usually being employed during the early stage of the pavement aging process and major rehabilitation when the chance to apply PM has been missed, as seen in Figure 8.

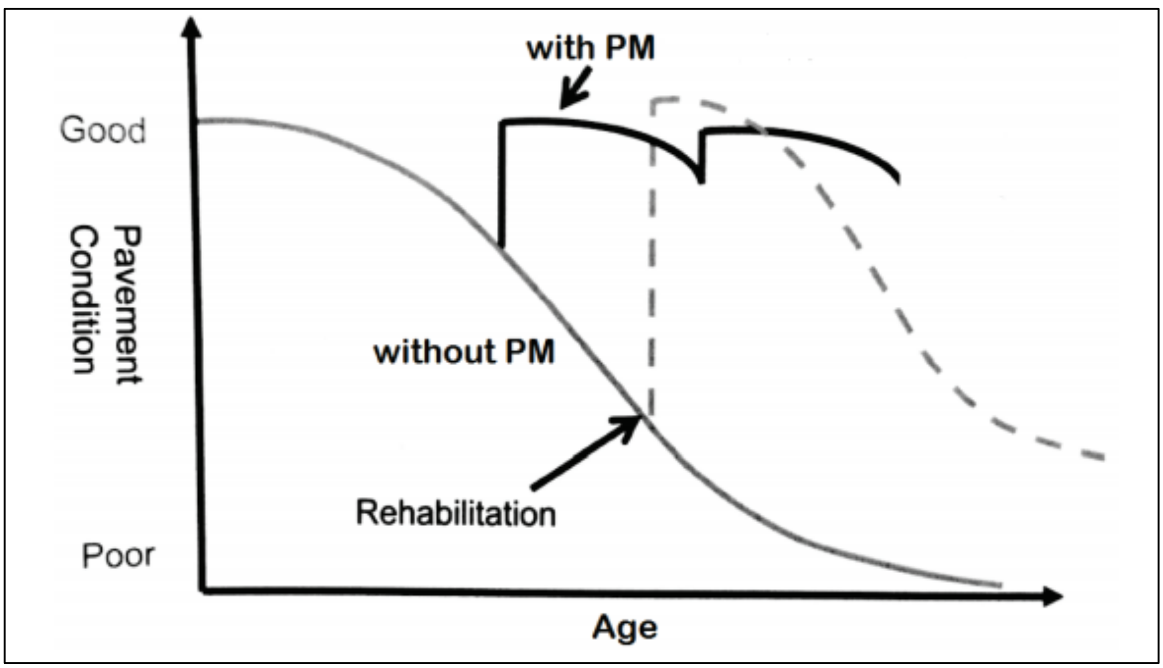

Figure 8: Theoretical Pavement Condition Deterioration Rate with and without M&R (Source: Chang et al., 2014)

It is important to remark that different pavements deteriorate at a different rate. For example, if two pavement sections start their service at the same time, it would be logical to think that after four years both would need the same M&R procedure. Nonetheless, it could be entirely possible that one of them only needs PM while the other requires major rehabilitation. Reasons for this are explored later on. In general, both PM and light rehabilitation are applied to the asphalt layer, with medium rehabilitation performed in the base or sub-base layers, and heavy rehabilitation involving also deeper work on the subgrade.

PM Treatment

Specific PM treatments exist for bituminous-surfaced and concrete-surfaced pavements, and may also include the maintenance of drainage features. They include cape seals, fog seals, seal coats, microsurfacing, thin overlays, ultra-thin friction course, cold in-place recycling, hot in-place recycling, mill and inlay, as well as a combination of two or more. This study is centered on three PM treatments commonly used in Texas for AC pavements: chip seals, microsurfacing and thin overlays. **¡Error! No se encuentra el origen de la referencia.** shows the conditions for use recommended by TxDOT, depending on four factors: the main distresses, traffic conditions, climate and restrictions.

Table 5: Conditions of Use Recommended by TxDOT for Different PM Treatments (based on TxDOT Guidelines to Assign PMIS Treatment Levels, 2014).

		Factor	Description
Treatment	Chip Seal	Main Distresses	• Light to moderate non-load related longitudinal, transverse, and block cracking. • Light to moderate raveling and flushing. • Temporary solution for light alligator cracking.
		Traffic	• Although used to treat roads with ADT>10,000, typically used when ADT<1,000 where chip seal is placed over and aggregate base or AADT<2,000 when placed over the existing asphalt layer. • Placed on roads with less than 15 percent truck volume or ADTT<250.
		Climate	• Perform well in all climatic conditions but special attention should be given during placement. They should be placed in warm weather with low humidity and wind, avoiding rainy cold conditions. • Not recommended after September or when freezing is expected within 48 hours.
		Restrictions	• Cracks wider than 0.125 inches should be sealed before their placement. • Not recommended for areas of frequent truck turning, breaking, accelerating and snow plowing areas. • Attention to traffic noise when treating high speed roads. • Existing pavement should have severe distresses patched.
	Microsurfacing	Main Distresses	• Used for low to medium severity transverse, longitudinal and block cracking. • Can stop raveling/weathering, low to medium bleeding, shallow rutting and low severity alligator cracking.
		Traffic	• Successful in both low and high volume roadways (typically AADT>400).
		Climate	• Effective in all climates, but performs better in warm temperatures with low daily variations. • Placement in hot weather to be avoided it there is potential for flushing. • Not recommended when freezing temperatures are expected within 24 hours since it can lead to early raveling.
		Restrictions	• Not effective against unstable rutting or rutting more than 1.5 inches and cracks more than 0.25 inches wide.
	Thin Overlay	Main Distresses	• Successful in treating low to medium severity transverse, longitudinal, and block cracking. • Addresses low to moderate raveling and low alligator cracking. • Extensive patching can also be treated.
		Traffic	• Performance not affected by AADT or percent trucks.
		Climate	• Performs well in all weather conditions. • Air temperature should be above 40 °F when placed, avoiding rain.
		Restrictions	• Candidate roads should have a stable pavement with a good base. • If surface is not uniform, special consideration to the grinding of the surface before placement should be taken. • When rutting is present, separate rut-filling applications are needed.

Chip Seal

A chip seal (also known as seal coat) is a surface treatment in which an asphaltic material (asphalt cement, cutback or emulsified asphalt) is sprayed over the pavement surface followed by a uniform graded aggregate cover (FHWA, 2015). It is employed to seal small cracks, waterproof surfaces and improve friction. It also provides a wearing course on low-volume roads (FHWA, 2015). TxDOT employs them to create a waterproofing membrane that protects the underlying material from moisture and erosion, which allows them to retain their strength, and at the same time reduces surface oxidation and bleeding.

Further, chip seals can improve surface friction and texture as well as being durable, with a low initial cost compared to other PM treatments, being widely available. On the other hand, their use may be discouraged are susceptible to stripping, do not improve ride quality, and cannot palliate cracks wider than 0.25 inches effectively. Their expected service life is in the order of three to eight years, but if placed over aggregate bases they will generally last a shorter period of time (TxDOT, 2014). Seal coats were traditionally placed using emulsion-bases binders although TxDOT is increasingly using hot-mix asphalt binders to reduce the time needed to open these to traffic, which is a major safety issue.

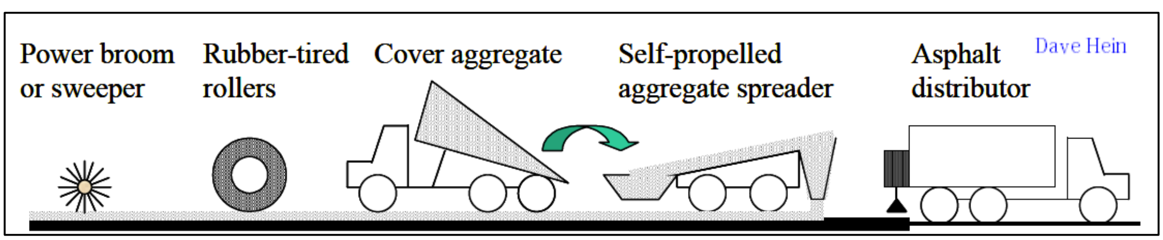

Figure 9: Application of Chip Seal

Microsurfacing

Microsurfacing comprises a mixture of polymer-modified emulsified asphalt, mineral aggregate, mineral filler, water, and emulsyfying additives. It is applied to prevent raveling and oxidation (FHWA, 2015). It has proved effective at improving surface friction, and filling minor irregularities and wheel rut.

Additionally, the treated section can be opened to traffic within an hour, and can improve ride quality. Microsurfacing usually performs well in areas of turning and stopping movements because of its higher shear strength. However, it can accelerate the development of stripping in susceptible pavements, and potential early damage in areas of heavy truck turnign and down grade locations. Microsurfacing lifespan is expected to be between three to eight years (TxDOT, 2014).

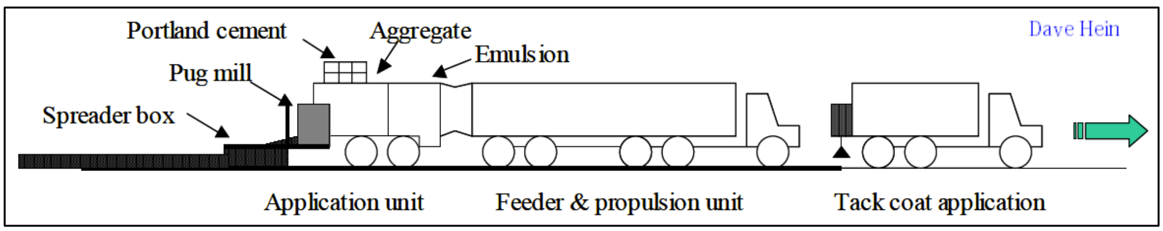

Figure 10: Application of Microsurfacing

Thin Overlay

Thin overlays consist of the application of hot-mix asphalt (HMA) overlay that is less that one inch in thickness (FHWA, 2002). It is placed to improve friction, correct surface irregularities and reduce surface permeability. TxDOT may use them as it enhances ride and surface friction, and can reduce hydroplaning and tire splash. Thin overlays can delay serious distreses, provide a protective waterproof membrane and correct surface irregularities.

A challenge may arise as they have a high initial cost and speciality contractors are required. Additionally, they may allow localized pavement faliures and deteriorated cracks to reflect through the new surface in an expedite manner. Their expected service life is generally in the order of seven to 10 years (TxDOT, 2014).

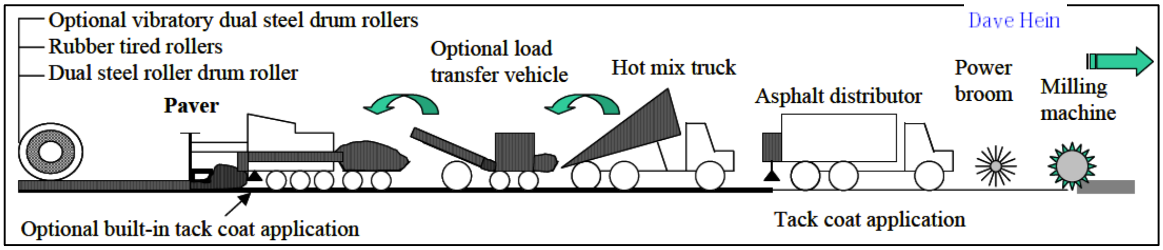

Figure 11: Application of Thin Overlay

Through the years, different experimental studies have been implemented to study these PM treatments, with chip seals being the most common approach and thin overlays having a relatively new status. Rajagopal (2010) found chip seals to be effective when the condition of the pavement is good, and microsurfacing being preferred when the condition is fair, but also that microsurfacing did not work well on principal roads, where traffic volumes and loads are high. Thin overlays have provided an unpredictable behavior, but generally working well for all kind of roads provided they are compacted properly. Chip seals have performed well in highways and high-volume roads (Hicks, 2000) and microsurfacing was an attractive option in areas with excessive turn movements, like signals. On the other hand, thin overlays exhibited permanent deformation when interacting with heavy traffic and high temperatures (Caltrans, 2009), providing the best results in areas with low traffic volumes.

Studies within the industry indicated that, from the applicability point of view, the placement of the PM treatments is simple, with the largest issue being dealing with the traffic during the construction stage (Braun Intertec Corporation, 2016). At the same time, while sections treated with chip seals can be re-opened to traffic almost immediately, microsurfacing requires time to build sufficient cohesion to avoid raveling due to traffic (Caltrans, 2009). No traffic should be allowed when thin overlays are placed until final rolling has been completed at the risk of undermining their performance.

MAJOR REHABILITATION

There are cases when applying PM treatments is not feasible, either because the opportunity to do so has passed, or the pavement deteriorated faster than expected. In these cases, pavement rehabilitation is necessary. TxDOT lists three rehabilitation types for asphalt pavement structures: light, medium and heavy (Chang et al., 2014).

- Light Rehabilitation – In general, is composed of non-structural improvements to address surface distresses, related to aging and environmental effects. Additionally, it restores functional characteristics and protects structural integrity. Ride quality can be expected to improve, but structural capacity will remain the same. The most commonly used light rehabilitation types by TxDOT are base repair and seal; mill and inlay; and mill, seal and thin overlay (Chang et al., 2014
- Medium Rehabilitation – Structural improvement to extend the service life of a pavement section and increase in its load-carrying capacity. This is achieved by increasing the pavement thickness, which allows the pavement to increase the vehicle loading and volume circulating. This type of rehabilitation also restores functional characteristics and so the ride quality is improved considerably. TxDOT generally employs base repair, spot seal, edge repair and overlay; level up and overlay; and mill and overlay (Chang et al., 2014).

- Heavy Rehabilitation – Consists of the partial or complete removal and replacement of the existing pavement structure as to restore both functional and structural conditions to at least the level of the original conditions. Good quality ride is restored, and all distresses are removed. This type of rehabilitation is required on pavement sections with extensive structural distress. In general, TxDOT would frequently employ full depth reclamation (pulverization and resurfacing); mill, cement stabilized base, and overlay; and reconstruction (Chang et al., 2014).

Life-Cycle Cost

The requirement to achieve the maximum benefit within a project, given the project is economically feasible as a whole, is one of the two levels of the application of principles of financial engineering to pavement projects. The other one is the determination of the feasibility and programing of the project (AASHTO, 1993). While project feasibility is determined at the network level by comparison with other potential projects. Within the project, economic viability is achieved by considering a variety of alternatives capable of satisfying the overall project target. Because in this work it is assumed a PM treatment would be applied when needed, the focus is on maximizing the economic benefit a project can deliver, notwithstanding the condition of other pavement sections that may also be in need of being treated or budget constraints.

It is essential that all costs incurred during the life of a PM treatment are included in its economic valuation (AASHTO, 1993). In fact, this had been so overlooked that in 1970 the term "life-cycle cost" was coined for use with pavements, which refers to all costs and benefits involved in a provision of a PM treatment, including, but not limited to, the cost of materials, equipment, transportation and construction, the value of money over time, interest rates, salvage or residual value, as well as agency and user costs. “Life-cycle cost” is a term coined to call attention to the fact that a complete, current economic analysis is needed if alternatives are to be correctly compared to each other (AASHTO, 1993).

Over the years, different methods to evaluate the economic worth of pavement assets over their life-cycle that can be applied to the different PM treatments were developed. These include cost-effectiveness, replacement analysis, break-even analysis, maximum benefit, least life-cycle cost, and life-cycle cost analysis.

Life-Cycle Cost Analysis

The Transportation Equity Act for the 21st Century (TEA-21) states the LCCA is a procedure for evaluating the total economic worth of a usable project segment by analyzing initial and discounted future costs, accounting for maintenance, usage, reconstruction, rehabilitation, restoring and resurfacing costs, over the lifespan of the studied project section. The application of LCCA to pavement-related research is not new. The American Association of State Highway Officials (AASHTO) introduced the concept in its “Red Book” (Babashamsi et al., 2016). Locally, the Centre for Transportation Research (CTR) and the Texas A&M Transportation Institute (TTI) developed the Flexible Pavement System (FPS), a computer-based approach to analyze and rate alternative flexible pavement designs according to their LCCA (Hudson and McCullough, 1970).

The implementation of LCCAs for pavements was popularized when the National Highway System (NHS) Designation Act of 1995 required state highway agencies to perform LCCA for every project segment (Kane, 1996). This requirement was waived in 1998, but its use is advocated by the FHWA. It stresses that, although the outcomes are not final decisions, the approach for analyzing the total economic value of a feasible project segment by evaluating the initial costs and discounting future ones, including maintenance can provide useful insight (Babashamsi et al., 2016).

LCCA is a decision-support tool frequently employed by transportation agencies to compare total user and agency costs for different project alternatives. LCCA is an economic analytical tool that compares benefits and costs for the different project alternatives, allowing decision makers to select the optimal option.

Many research efforts have produced knowledge aimed at improving the LCCA of pavements. Some recent studies contributed by exploring sequential patterns of pavement treatments (Jeong and Pour, 2012), exploring how governmental agencies can benefit from it (Arditi and Messiha, 1999), studying management strategies that consider LCCA (Ding et al., 2013), and developing sensitivity analyses for the factors affecting them (Ferreira and Santos, 2013). Walls and Smith (1998) presented technical instructions to perform LCCA accurately, in their Technical Bulletin of 1998, aimed at state highways personnel performing it (Babashamsi et al., 2016). This thesis intends to build on this previously developed knowledge and develop a probabilistic LCCA framework that helps to evaluate and compare systematically pavement sections subjected to one of the three evaluated PM treatments – using TxDOT data – and identify the factors affecting their performance.

The FWHA defines two approaches to prepare a LCCA: deterministic and stochastic or probabilistic. The methods differ in the manner they address the variability and uncertainty associated with the LCCA input parameters including activity cost, activity timing, and discount rate.

DETERMINISTIC LCCA APPROACH

The deterministic LCCA involves the use of fixed input values that result in deterministic output values. The value for each input parameter is usually estimated based on either historical evidence or engineering judgment (FHWA, 2002). Sensitivity analyses conducted to test input assumptions by varying one input while holding other inputs constant should be conducted as a minimum requirement in deterministic LCCAs. This helps to determine the effect of the variation of parameters in the outputs.

Some flaws in the deterministic approach include its failure to address simultaneous variation in multiple-input cases, as well as the inability to convey the degree of uncertainty associated with the LCC estimates. In other words, with the deterministic method only one deterministic result is evaluated by using only one representative value for each time and cost parameters of the model, which can lead to debate on the validity of the results (Cho, 2008). Dependence on deterministic LCCA raises issues about the accuracy of input information because, for example, of the degree of construction price volatility found in the underlying commodities used in pavements (Pittenger et al., 2012).

STOCHASTIC LCCA APPROACH

The stochastic or probabilistic LCCA allows the value of individual input parameters to be defined by a frequency (probability) distribution (FHWA, 2002). The probabilistic LCCA is more robust than the deterministic one, and involves the modeling of uncertainty as it takes probabilities into account (Pittenger et al., 2012). It is also more complex to perform.

To characterize these uncertainties, a stochastic LCCA approach combines probability descriptions of random variables and computer simulation techniques, with a method commonly known as Monte Carlo Simulation (MCS)

(Walls and Smith, 1998). Further, this method also allows to acquire information like the distributions of the LCCA which is useful to run sensitivity analysis (Cho, 2008). The stochastic approach allows to take full advantage of the gathered data as a distribution to describe the cost and effective life of the treatments during the simulation. Additionally, stochastic LCCA has been shown to produce superior results when used at the new pavement design or network level, and its use for transportation is advocated by the FHWA (Pittenger et al., 2012).

Life-Cycle Cost Analysis Methodology

The FHWA developed a methodology to estimate LCCAs for different alternatives, synthesized in five steps, including establishing design alternatives, determining activity time, estimating costs, computing life-cycle costs and analyzing the results.

1. Establish Design Alternatives

The LCCA process is initiated after an asset has been selected to be improved and a range of possible alternatives have been identified to help accomplishing that improvement (FHWA, 2002). Each design alternative will have an expected initial design life, periodic maintenance treatments, and often a series of rehabilitation activities (Walls and Smith, 1998). At least two mutually exclusive options ought to be considered. The economic difference between alternatives is then assumed to be attributable to the total cost that each of them represents (FHWA, 2002). More often than not, the identification of maintenance and rehabilitation activities is based on all historical practice, research, and agency policies.

2. Determine Activity Timing

The service life of the initial pavement design and subsequent rehabilitation activities have a major impact on the LCCA outcomes as they directly affect the frequency of agency intervention. These will in turn affect agency costs along with user costs during the periods when the pavement is subjected to construction and maintenance activities (Walls and Smith, 1998). The timing of rehabilitation activities should be based on existing performance records (FHWA, 2002).

3. Estimate Costs

LCCA considers costs accrued to highway agencies and to users of the highway system, as a result of agency construction and maintenance activities. LCCAs do not require all costs to be associated with each alternative to be calculated. Only costs demonstrating differences between alternatives need be explored (FHWA, 2002). Costs common to all alternatives cancel out and these cost factors are consequently excluded from the LCCA calculations (Walls and Smith, 1998).

4. Compute Life-Cycle Costs

Projected activity costs for alternatives need to take into account the value of money over time. Methods from the field of economics are used to transform anticipated future costs to present money value, so that the lifetime costs of different alternatives can be compared in a direct manner (FHWA, 2002).

The most common methods include Benefit/Cost (B/C) Ratios, Internal Rate of Return (IRR), Net Present Value (NPV), and Equivalent Uniform Annual Costs (EUAC). The B/C analysis represents the net discounted benefits divided by net discounted costs for a given alternative. This methodology is not recommended for pavement analysis because of the difficulty in sorting out reliable benefit and cost estimates (Chang et al., 2008).

The IRR represents the discount rate necessary to make discounted cost and benefits equal. While this index does not provide a final decision criterion, it provides useful information, particularly when budgets are constrained, or if the accuracy of the adopted discount rate is doubtful (Walls and Smith, 1998). NPV and EUAC are typically used to convert cost streams into a single economic value by using a discount rate that resembles reality in a reliable manner (Beg et al., 1998).

Net Present Value

The Net Present Value (NPV) or Net Present Worth (NPW) is the discounted monetary value of the expected net benefits. The NPV for the lifespan of a pavement section can be estimated using Equation 2.7. Present-worth costs of the strategies provide a fair comparison basis (Beg et al., 1998). There is a fairly strong agreement in the literature that NPV should be the economic indicator of choice. Continuous compounding Equation 2.8 should be implemented when the time interval is not defined in round years.

$$\mathrm{NPV} = \mathrm{Initial\ Cost} + \sum_{k=1}^{N} \mathrm{Rehab\ Cost}_k \left[\frac{1}{(1+i)^{n_k}}\right] \tag{2.7}$$

$$\mathrm{NPV} = \mathrm{Initial\ Cost} + \sum_{k=1}^{N} \mathrm{Rehab\ Cost}_k \left[\frac{1}{\exp\,(i * n_k)}\right] \tag{2.8}$$

Where:

i= discount rate

n=year of expenditure

Equivalent Uniform Annual Costs

The Equivalent Uniform Annual Cost (EUAC) combines every NPV obtained for all discounted costs for a studied option and the benefits of an alternative to that option into equal annual payments over the analysis period. It can be calculated by estimating the NPV in the first place and implementing Equation 2.9 afterwards.

$$\mathrm{EUAC} = \mathrm{NPV}\left[\frac{\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}}-1}\right] \qquad (2.9)$$

Where:

i= discount rate

n=analysis period

5. **ANALYZE RESULTS**

Once the deterministic or probabilistic LCCAs have been computed, the NPVs of the differential costs may be compared across competing alternatives (FHWA, 2002). The probabilistic approach yields a distribution of NPV results, allowing for comparison.

Chapter 3: Information Gathering and Breakdown

In this thesis, the LCCA was performed using PM treatment data processed from TxDOT databases and information systems containing historical data of M&R projects constructed between 1994 and 2015. These databases are operated and maintained through a statewide computer network that allows all districts and Austin headquarters to maintain project data in a common format. Only PMs applied to AC pavements were considered. The information considered for the analysis was collected from multiple databases. These include Design and Construction Information System (DCIS), Pavement Management Information System (PMIS), Maintenance Management Information System (MMIS), SiteManager (SM) and Compass. The final, compiled database was build based partially on the procedures developed in previous work conducted at UT Austin (Prozzi el al., 2017b; Serigos, 2016).

The available information comprises 14,000+ PM treatment projects, and is limited to chip seals, microsurfacing and thin overlays. The data available on the effective life comprises both censored and non-censored information that includes surfaces monitored during or throughout their service lives. Statistically speaking, censoring is a condition in which the value of a measurement or observation is only partially known (Milner et al. 2017). Censoring occurs when a subject (in this case a treatment) leaves the study before an event occurs (in this case the end of the effective life), or when the study ends before the event has occurred (Lunn, 2007). Those treatments that did not reach the end of their effective life by the end of the year 2015 were censored.

The processed data also included cost information, which refers to the cost – in dollars per lane mile – of implementing PM treatments. Additionally, it contained the type of facility and traffic information such as: traffic volume

(AADT); traffic loads (ESALs). The LCCA performed here only considered PM treatment projects that were applied on structurally sound pavement sections – not in need of structural reinforcement. This ensured that the section was in a "Good" condition. For this condition, neither minor light, medium or heavy rehabilitation projects need to be implemented.

TxDOT information systems and databases containing information on the M&R implemented during past years can be divided into two groups (Serigos, 2016). In the first one are the Design and Construction Information System and SiteManager. They only contain data involving contracted projects. In the second group, Maintenance Management Information System and Compass are included. They only contain data from internal – also referred to as "in-house" – projects, performed by TxDOT personnel. In general, contracted projects are larger than in-house ones and thus lengthier and more expensive to perform. Data emanating from contracted projects was the main source of information, but in-house projects were also included. Contracted projects usually contain more precise and detailed information. This is because sometimes in-house project information is neglected to be collected – or not done in an accurate manner. However, TxDOT requires accurate information on contracted projects so that it can track the progress and costs during construction.

Pavement information is collected in the field every year in all public roads in Texas managed by TxDOT and stored in the PMIS database. This contains information on both contracted and in-house projects. Information on projects contained in these three databases – DCIS, PMIS and SM – can be linked together using the respective control section job (CSJ) number and Texas Reference Markers (TRMs) indicating the beginning and ending extents of the project. Each PM treatment that has been applied is kept on record via its CSJ, so that the pavement section on which they were applied is known.

DESIGN AND CONSTRUCTION INFORMATION SYSTEM (DCIS)

The DCIS is TxDOT's database used for planning, programming, and developing projects. It is an essential part of preparing construction projects for contract letting. This means information of PM treatments that were not performed by TxDOT is found here. Project information includes work descriptions, funding requirements, and dates for proposed activities. In other words, DCIS has "as designed" information for contracted projects, together with cost tracking- information (Serigos, 2016). Relevant information also contains the CSJ, the location, the project completion year, items and quantities. The highway number and the TRMs help to locate the project. The beginning and ending TRM number are also contained in the database. Finally, the district and county names, project length, description and highway number are stored in DCIS as well. Relevant items contained on this database are summarized in Table 6.

Table 6: DCIS Database Relevant Information (Based on: Prozzi et al. 2017a)

ID	Description
CSJ	Control Section Job Number
DISTRICT	District Name
COUNTY	County Name
PROJ_LENGHT	Project Length
PROJ_DESC	Project Description
HWY_NUM	Highway Number
BEG_REF_MARKER_NBR	Beginning TRM - Integer Part
BEG_REF_MARKER_DISP	Beginning TRM - Decimal Part
END_REF_MARKER_NBR	Ending TRM - Integer Part
END_REF_MARKER_DISP	Ending TRM - Decimal Part

The TRM number indicates a physical marker on the highway. These are usually placed on sign posts, spaced approximately every two miles along the road. The TRM displacement is a measured displacement in miles from this physical marker. TxDOT´s Transportation Planning and Programming Division derived the initial TRM numbers for a highway by imposing a grid on a map of Texas (Figure 12). TRMs increase north to south and west to east, depending on the highway's general direction, except north-south interstates, where numbers increase south to north (TxDOT, 2015). The numbers are continuous from the route beginning to its ending. They do not reset to zero at county lines. All routes, regardless of length, must have at least one TRM (TxDOT, 2015).

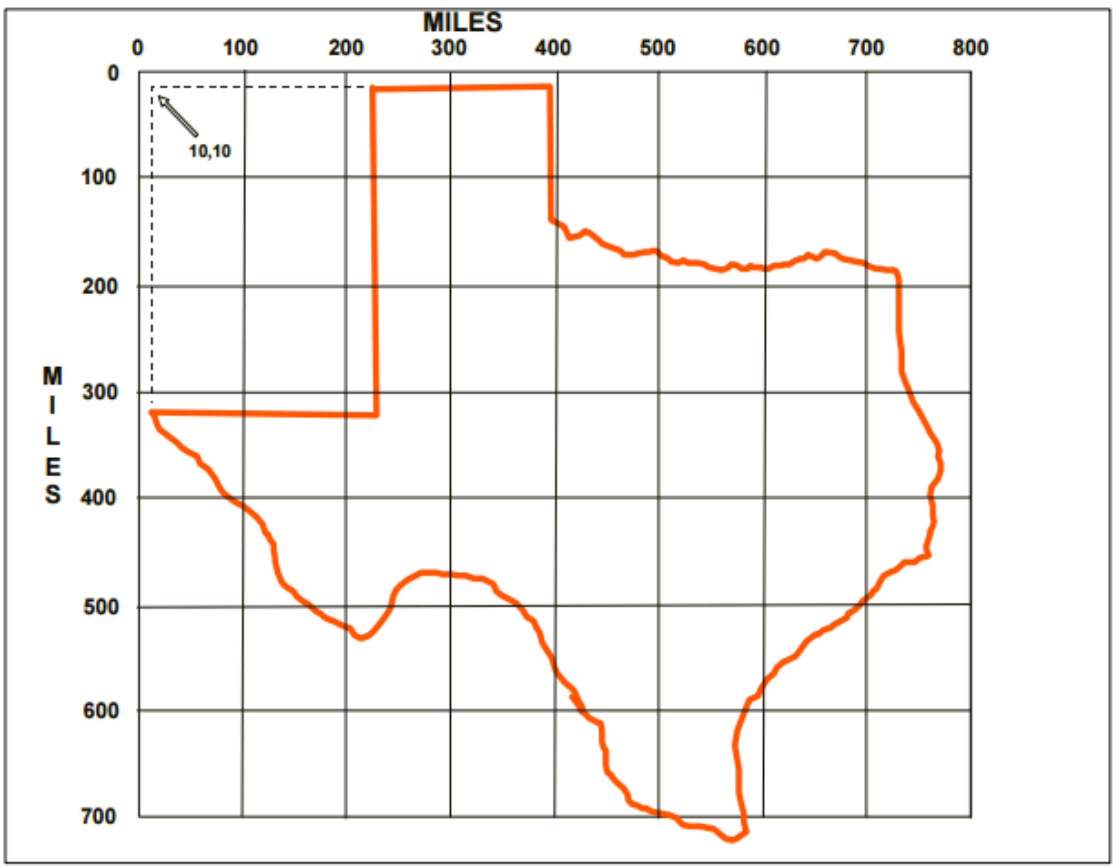

Figure 12: Texas Reference Marker Grid (Source: TxDOT, 2015).

Pavement Management Information Systems (PMIS)

The PMIS is a system for storing, retrieving, analyzing and reporting information to help with pavement-related decision-making processes. PMIS contains the annual pavement performance measurements collected by TxDOT across the Texas highway network (Prozzi et al., 2017a). PMIS data is collected on over 90 percent of the TxDOT roadbed mileage each year. The combination of on-going construction project work zones, accidents, and very heavy traffic in metro Districts makes data collection on the 100 percent of the state pavement network impossible (Zhang and Murphy, 2012). PMIS data includes distress data collected between September and December by contract raters. In addition, automated ride quality and rutting information is collected using TxDOT profiler/rut-bar vans.

The PMIS database serves as a statewide memory bank for TxDOT containing information dating back to 1984. Pavement distress and condition information started being collected in its current format in 1994. Data for each 0.5-mile PMIS rating section is supplemented with information obtained from the TxDOT TRM database, and includes traffic volumes and loads, posted speed limit, and other factors (Zhang and Murphy, 2012).

This database contains information on the project specifications and data collection year, the highway number and roadbed type, beginning and ending TRM numbers and pavement types (this thesis only considers AC ones). Current traffic information – AADT, ESALs and speed – is also stored here. It also contains pavement condition and distress scores and IRI. Pavement condition measurements stored in the PMIS database are used to monitor the highway network and to schedule maintenance activities accordingly (Prozzi et al., 2017a). Items that were considered for this work are shown in Table 7, along with their description.

Table 7: PMIS Database Relevant Information (Based on: Prozzi et al. 2017a)

ID	Description
CSJ	Control Section Job Number
FISCAL_YEAR	Data Collection Tear
SIGNED_HIGHWAY_RDBD_ID	Highway Number and Roadbed ID
BEG_REF_MARKER_NBR	Beginning TRM - Integer Part
BEG_REF_MARKER_DISP	Beginning TRM - Decimal Part
END_REF_MARKER_NBR	Ending TRM - Integer Part
END_REF_MARKER_DISP	Ending TRM - Decimal Part
PVMNT_TYPE_BROAD_CODE	Pavement Type
AADT_CURRENT	Current Annual Average Daily Traffic
CURRENT_18KIPS_MEAS	Design Equivalent Single Axle Load
SPEED_LIMIT	Speed Limit
NUMBER_THRU_LANES	Number of Traffic Lanes
CONDITION_SCORE	Condition Score
DISTRESS_SCORE	Distress Score
RIDE_SCORE	Ride Score
IRI_LEFT_SCORE	IRI on Left-Wheel Path
IRI_RIGHT_SCORE	IRI on Right-Wheel Path

SITEMANAGER (SM)

SM is a database used by TxDOT to store the material information at the item level. This is to say, the each material and its associated characteristics is specified. While DCIS has “as designed” information for contracted projects, SiteManager has “as constructed” information (Serigos, 2017). SM data was used to confirm that a project appearing in DCIS was completed and obtain more detailed information regarding the completion date (Serigos, 2017). SM was used to retrieve information on the end of the effective life of PM treatments. Information contained in SM includes asphalt mixture properties such as binder content, mixture air voids and density, aggregate specific gravity and other material information (Prozzi et al., 2017a). Among the items included to describe them are the design gyrations, the binder performance grades, the sieving of the filler, and aggregate specifications. Factors such as maximum specific gravity, mixture density and voids in both aggregate and asphalt – in laboratory and in the roadway – are also here.

Fields relevant for this work included CSJ, project control numbers and item codes. Additionally, the project’s year of replacement and PM treatment type were stated. In the cases when the PM treatment had not yet been replaced, the year of replacement was substituted with the year in which the project was accepted by TxDOT (Prozzi et al., 2017).

In addition, SM contains information gathered on projects from engineers and contractors during construction. This includes design as well as quality control and assurance (QCQA) data. The SM database stores the sequence of the items in an increasing order, which helps TxDOT to keep track of all change orders of its projects. Important information contained in SM for this thesis is presented in Table 8.

Table 8: SM Database Relevant Information (Based on: Prozzi et al. 2017a)

ID	Description
CSJ	Control Section Job Number
ITM_CD	Item Code
COMPL_YR	Project Completing Year
MIX_TYPE	Mixture Mix Type
PG_CLEANED	Binder Performance Grade

Decision to Implement a PM Treatment

TxDOT has implemented the four-year plan. The plan is relatively new and can be enhanced, and information on how it works is not public domain. Addressing this shortcoming, this work used the concept of "effective life" to decide when to substitute an existing PM treatment. This allowed for a cost-effective manner for treatment substitution: before the pavement section required major rehabilitation, but avoiding to replace it before it was necessary.

EFFECTIVE LIFE

The expected or service life of PM treatments is the number of years the treatment will be functionally in an acceptable condition with only routine maintenance (Balla, 2010). This makes service life a fundamental input in the LCCA analysis. It gives a sense of how long a PM treatment could last once it is implemented, and indicates when it has to be substituted. This thesis characterized the service life of the PM treatments based on their effective life. The effective life of each PM treatment was defined as the time that elapses between two consecutive treatment applications. In other words, it was the time lapse between the application of the treatment and when another surface was applied over it (Serigos et al., 2017).

To estimate the effective life of the PM treatments comprised in the TxDOT databases, survival analysis was conducted on the processed TxDOT data. This allowed to include cases for which end-of-service life had not yet been reached (Serigos et al., 2017). Treatments in this situation were referred to as censored observations, and including them in the analysis delivered more robust and unbiased estimates of the effective life of the treatment (Serigos et al., 2017).

The high variability in the effective life data favored the stochastic LCCA approach as the preferred analysis option because it allowed the use of probability distributions to estimate the distribution of the life of a treatment, as opposed to the defined service-length values required with the deterministic LCCA approach. Traditionally, the probability distributions for the service effective life of different PM treatments have been defined using a triangular distribution, which has tail values that increase and decrease linearly (Walls and Smith, 1998). The triangular distribution needs to have minimum, median and maximum values as input parameters. This allows to avoid negative service life values and its symmetry has the added advantage of not giving more weight to a particular alternative based on the influence of higher or lower discount rates. Typically, lower discount rates favor higher initial costs and lower future costs. Higher discount rates in turn favor lower initial costs and higher future costs.

Even when the triangular distribution could provide a good estimate of the effective life of a PM treatment, it is not natural. Further, once a minimum value has been defined, the distribution increases linearly until the median point is reached. In the same fashion, from the median value it decreases linearly to the maximum point. However, it is possible that a treatment could perform worst that what TxDOT databases have detected so far, or better.

In this analysis, the gamma and Weibull distributions were considered to estimate the effective life based of the PM treatments. Although the information collected on the effective life for this work was extensive enough to assume normal distribution, employing a normal distribution was discarded because it would allow obtaining negative values, and the effective life of the treatments is by definition non-negative. Further, the normal distribution is bell-shaped and therefore symmetric (Devore, 2012). The observed distribution of the effective life of PM treatments in Texas is quite asymmetric.

GAMMA DISTRIBUTION

The gamma family of distributions is used as a model for the distribution of times between the occurrence of successive events (e.g. customers arriving at a service facility) (Devore, 2012). This is because it is closely related to the Poisson Process. To define the gamma distribution and its family, it is first necessary to introduce the gamma function – represented by Γ(α) and defined only for α greater than zero – in Equation 3.1.

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx \tag{3.1}$$

Then, a continuous random variable X is said to have a gamma distribution if the PDF is:

$$f(X; \alpha, \beta) = \begin{cases} \frac{1}{\beta^\alpha \Gamma(\alpha)} X^{\alpha-1} e^{-\frac{x}{\beta}} & X \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{3.2}$$

Where:

α, β – parameters (greater than zero)

$\Gamma(\alpha)$ – gamma function

In cases where parameter β is equal to one, the distribution is known as the standard gamma distribution, and its PDF can be expressed in Equation 3.3.

$$f(X;\alpha) = \begin{cases} \dfrac{X^{\alpha-1}e^{-X}}{\Gamma(\alpha)} & X \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{3.3}$$

For standard gamma PDFs, if α is equal or less than one, the PDF will be strictly decreasing. For values of α greater than one, the PDF will rise from zero at X equal to zero to a maximum value and then start decreasing. β is thus the scale parameter for this distribution. For this, a value of β other than one, will either stretch or compress the PDF in the X direction. The expected value and variance for a random variable X having the gamma distribution can be expressed in terms of the parameters α and β such that:

$$E(X) = \mu = \alpha\beta$$

and, $$V(X) = \sigma^2 = \alpha\beta^2 \tag{3.4}$$

WEIBULL DISTRIBUTION

Although the gamma distribution family provides many probability models for continuous variables, there are practical applications in which they do not fit the data well enough. Swedish physicist Waloddi Weibull introduced the Weibull distribution in 1939. A random variable X is said to have a Weibull distribution if the PDF of X is:

$$f(X;\alpha,\beta) = \begin{cases} \frac{\alpha}{\beta^{\alpha}} X^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}} & X \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{3.5}$$

Where:

α – shape parameter (greater than zero)

β – scale parameter (greater than zero)

In some situations, there are theoretical justifications for the appropriateness of the Weibull distribution, but in many cases it simply provides a good fit to the observed data for particular values of α and β (Devore, 2012). The expected value and variance for a random variable X having the Weibull distribution needs the use of the gamma function, and can be expressed in terms of the gamma function, and the parameters α and β, such that:

$$E(X) = \mu = \beta\Gamma(1 + \frac{1}{\alpha})$$

and, $$V(X) = \sigma^2 = \beta^2 \left\{ \Gamma\left(1 + \frac{2}{\alpha}\right) - \left[\Gamma\left(1 + \frac{1}{\alpha}\right)\right]^2 \right\} \tag{3.6}$$

The Weibull distribution was originally proposed to quantify fatigue data, but it was also used in analysis of systems involving a "weakest link". It could then be employed to model the distribution of lifespan of different assets. For this reason, the Weibull distribution will be used to model the distribution of the effective live of a PM treatment.

Costs

The cost of each project is the total, final cost after the PM treatment was applied and all factors were considered and included. It is important remember, PM treatments need to be applied before major rehabilitation is necessary, and the pavement section has to be structurally sound, as PM treatments cannot provide structural reinforcement. The timely implementation of PM treatments will usually prevent the need for major rehabilitation – with the main benefit being that PM is expected to be more cost-effective than major rehabilitation. To reduce bias in the comparison of the treatment costs, these are transformed into their 2016-dollar value. This is achieved by applying the Inflation Index suggested by the United States Bureau of Statistics pavement segment (U.S. Department of Labor, 2016) for each analyzed pavement segment.

The PM treatment costs are very variable even within the same PM treatment category because there exists additional variation within and between them, besides inflation. This variation could be attributed to many factors. The most important are the dissimilar duration of the applied PM treatments, fluctuation in the pricing of asphalt raw materials over time, geographic location of the project and employed workforce and equipment.

- Variable duration of PM treatments – some treatments last longer than others. For example, on average TxDOT lists the expected life of chip seals and microsurfacing at three to eight years and that of thin overlays at seven to ten years. This may change depending on the condition of the pavement base, the evolution of traffic and load patterns, and climatic conditions. The more often a PM treatment needs replacement, the less cost-effective it becomes.

- Fluctuation in the pricing of asphalt raw materials over time – asphalt and derivatives costs are dependent on the crude oil price, which is not steady and whose changes are difficult to predict. The cheaper the crude oil is, the less effect on the cost of the application of PM treatments binder and other raw materials have.
- Project location – it is more cost-effective to apply PM treatments in good quality subgrades. Because it would be economically impractical to transport material from good-quality quarries available, material near the project location is almost always used. Climatic conditions such as temperature, rain and snow also affect the performance of the treatments (Serigos et al., 2017). Additionally, traffic handling is less costly in low volume roads and thus incur lower user costs.
- Workforce and equipment – the more isolated the treated section, the more difficult and costly is to either find local workers or to transport them to their work place. Transportation of equipment could be costly and may require specialized machinery operators. Also, the more widespread the use of a PM treatment is, the more automated the construction process is and less mistakes are committed compared to a treatment involving a convoluted process.

In the same way effective life favored a stochastic LCCA approach, the project cost was modeled using probability distributions and not deterministic values in order to take cost variabilities into consideration. In general, normal distributions are used to estimate the costs of PM treatments as there is sufficient data to assume the distribution is normal. The parameters required by this distribution are the mean and standard deviation, which are relatively easy to estimate.

It is further suggested to make use of triangular distributions as a rough estimate of the shape of the distribution – and even uniform distributions –when nothing is known about the shape of the information that is to be analyzed (Walls and Smith, 1998). Although a large volume of TxDOT data on the costs of PM treatments was collected to assume a normal distribution, the use of the lognormal probability distribution was considered more appropriate.

Normal distribution could resemble cost distributions, but it is bell-shaped and negative values are likely to be obtained during the simulation, even if the probability is small. Additionally, the shape of the normal distribution does accommodating extreme values, which have been detected during the process of compiling the database. Another potential problem that could arise with normal distributions is that, given the median costs are equal to the mean costs, results obtained could be misleading or difficult to interpret. This is because mean costs are prompt to be affected by outliers, while the median costs will stand relatively steady, and so a distribution that differentiates mean and median would be better to describe the results. For this study, median was the statistical indicator of choice. A natural choice would be to model the costs using TxDOT maintenance databases with a lognormal probability distribution, which addresses the issues presented above while its logarithm is still normally distributed, and thus complies with the central limit theorem.

LOGNORMAL DISTRIBUTION

A lognormal probability distribution avoided simulating negative costs as logarithms can only take positive real values. Lognormal distributions could either be skewed to the right or to the left so that the mean is not equal to the median, and have long or short tails – depending on the data (long tails in this case). This better represented the extreme values which were detected for the costs. Finally, this distribution presented a mathematical advantage as it allowed to use transformations to estimate costs parameters linearly. The inputs required for a lognormal probability distribution were mu and sigma, which are the mean and standard deviation, respectively, of the associated normal distribution. Both distributions are continuous, a necessary condition for the used data.

Formally, a non-negative variable X is said to have a lognormal distribution if Y=ln(X) has a normal distribution (Devore, 2012). The resulting PDF of a lognormal variable when ln(X) is normally distributed with parameters μ and σ is shown in Equation 3.7.

$$\mathrm{f}(X;\ \mu,\sigma) = \begin{cases} \dfrac{1}{\sqrt{2\pi}\,\sigma X} e^{-\frac{[\ln(X)-\mu]^2}{2\sigma^2}} & X \geq 0 \\ 0 & \text{otherwise} \end{cases} \qquad (3.7)$$

Where:

μ – mean of ln(X)

σ – standard deviation of ln(X)

Further, the mean and variance of X for the lognormal distribution can be expressed as:

$$\mathrm{E}(X) = e^{\mu+\frac{\sigma^2}{2}}$$

and $$\mathrm{V}(X) = \sigma^2 = e^{2\mu+\sigma^2} \qquad (3.8)$$

Figure 13 shows the normal and lognormal distribution when the mean and standard deviation are the same for both – mean equals five and standard deviation equals two. As it can be seen, the normal distribution is bell-shaped centered on the mean and has negative values. The mean and the median are the same. Although the number of values on the tails is low, it is non–zero. On the other hand, the lognormal distribution has only non-negative values, and it is not centered on the mean. It is skewed to the right with a longer tail and the median is lower than the mean.

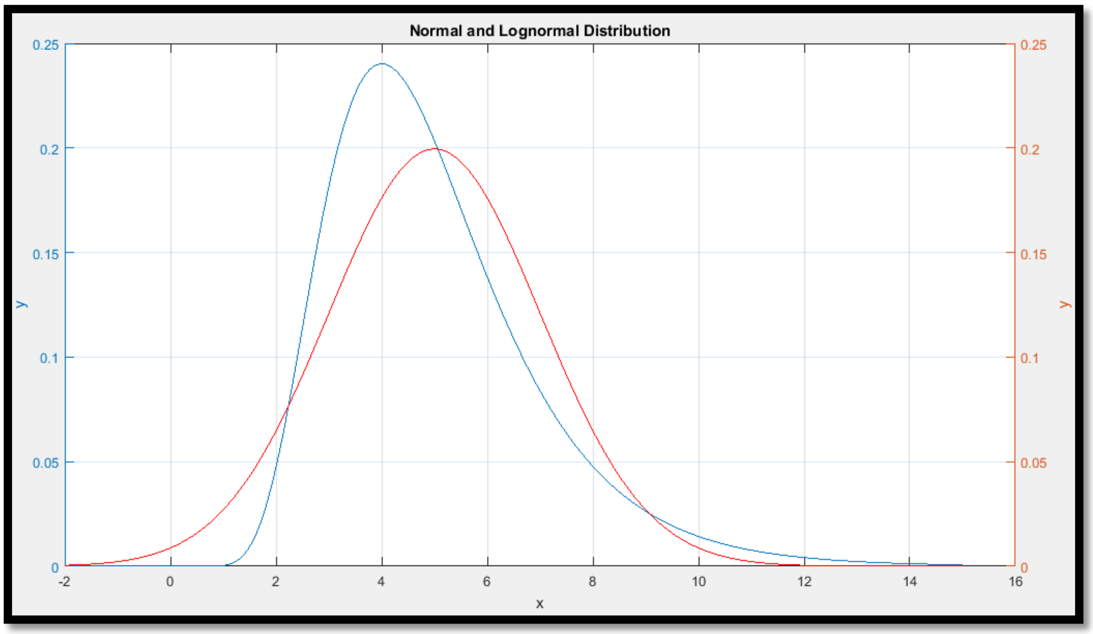

Figure 13: Normal Distribution (Red) and Lognormal Distribution (Blue) for Mean Five and Standard Deviation Two

Traffic Information

Pavement PM treatments help reduce the amount of water infiltrating the pavement structure, slow the rate of deterioration or correct surface deficiencies such as roughness and non-load distresses, but they do not contribute to the improvement of the pavement structure (ODOT, 2001). The effective life of a pavement surface depends heavily on wear and tear caused by traffic volume and loads. If a treatment is located on a road that is seldom used it will, in general, have a longer effective life than one located on a busy road. In the same way, it is expected that the heavier the loads applied to a treated section the faster the treatment will need to be replaced.

In order to analyze the impact of traffic usage and loads on the effective life and cost of PM treatments, this study quantified the effect of traffic on cost. Several traffic indicators were developed to describe traffic information based mainly on the traffic volume and loads, and on the highway design and intended use. These indicators include AADT, ESAL, highway designation, percentage of trucks, level of service (LOS), equivalent single wheel load (ESWL), nationally designated truck routes, K-Factors, and vehicle damage factor.

- Percentage of trucks – Because trucks are more prone to damage the pavement surface, it describes the share of trucks using a highway segment during the 30^{th} highest traffic hour of the year.
- Level of service (LOS) – The Highway Capacity Manual states LOS is a function of volume and capacity, as shown in Table 9. It is used to analyze highways by categorizing traffic flow and assigning level based on performance measures like speed and density. As most people travelling by automobile in the U.S. do it alone (Grava, 2002) the LOS on the available facilities to decrease and thus the pavement surfaces are damaged faster.

Table 9: LOS Classification (Based on the Highway Capacity Manual)

LOS	Quality	(mph)	Description
A	Free-flow	50	High level of physical and psychological comfort
B	Reasonable Free-Flow	43	Reasonable level of physical and psychological comfort
C	Near free-flow	37	Local deterioration possible with blockages
D	Medium flow	31	Non-recoverable, local disruptions
E	At capacity flow	25	Minor disturbances, resulting breakdown
F	Congested flow	9	Break down of flow, capacity drops

- Equivalent single wheel load – Considers the most adverse loading case of breaking, which is maximum in the front wheels and decreases in the rear wheels. The loading of each wheel is determined by considering its relative distance from the center line of the vehicle, deriving it from the heaviest wheel load. Then the four or more load values which will pass over one spot are expressed as the equivalent number of passes of the highest wheel load (Knapton, 1999).
- Nationally designated highway routes – Defined as routes designated for use by dimensioned commercial vehicles under the Surface Transportation Assistance Act (STAA) of 1982. They include the Interstate System and Federal-aid Primary (FAP) routes, which excludes some roads that may be of interest (FHWA, 2014).
- K-Factor – Describes the traffic volume on a road based on the annual 30th busiest hour as a percentage of the AADT. An Automatic Traffic Recorder (ATR) is needed for continuous traffic monitoring, making it expensive. This leads to the use of estimated K-Factor values which have only proved useful for low volume roads (FHWA, 2014).

- Vehicle damage factor – Converts the number of commercial vehicles of different axle loads and configurations to the number of ESAL repetitions, defined as equivalent number of standard axles per commercial vehicle. It varies with the axle configuration, axle loading, terrain and type of road (NPTEL, 2009).

Many of these indicators are either based on other indicators, have evolved, have limited reach or leave pavement segments that could be of interest out. TxDOT generally has defined indicators for highway design and monitoring on its information databases. By combining available information and relevance of the indicators in Texas, three were selected for the simulation: AADT, ESAL and Highway Designation or roadbed.

ANNUAL AVERAGE DAILY TRAFFIC

AADT measures how busy a particular road is. AASHTO defines AADT as the total volume of traffic on a highway segment in one year, divided by 365 days (Huang, 2004). This information can be obtained from traffic counts. These counts must be adjusted in order to account for daily (i.e. weekday versus weekend), seasonal variations (e.g. summer versus winter), and vehicle classification (Huang, 2004).

For TxDOT, AADT is a twenty-four-hour axle count for a segment of roadway to which seasonal factors and axle correction factors are applied during development. AADT can be divided into different categories. Historic AADT may be used to develop growth factors for estimating current and future AADT, with current AADT being the most recent estimate for a roadway segment. Forecasted AADT is a twenty-year projection of AADT development using linear regression and ten years of historic AADT. Finally modeled AADT computes the AADT produced by travel demand models. AADT is relevant since TxDOT keeps a detailed count of the AADT on all of its maintained roads. One of its most important uses is to help determining funding for the maintenance of roadways.

EQUIVALENT SINGLE AXLE LOAD

Wheel loads act at different points of the surface pavement and cause deformations. There are several wheel arrangements (i.e. single wheel, dual wheel, single axle, tandem axle, etc.). The lower the wheel load the less a pavement stresses and thus the longer it lasts (Wisconsin Transportation Bulletin No.2). For this, trucks are the primary concern and so the Texas Department of Motor Vehicles (TxDMV) has established size and weight limits for vehicles and loads based on the vehicle type and number of axles. Even when determining a wheel or an axle load for an individual vehicle may not be over challenging, it may become complicated to determine the number and types of wheel/axle loads that a particular pavement section will be subjected to (Pavement Interactive, 2012).

ESAL is a concept developed after the AASHO Road Test in the 1960's to establish a pavement damage relationship that compares the effects of different axles carrying different loads. The reference axle load is an 80 kN (18,000-lb) single axle with dual tires (Huang, 2004). TxDOT uses this measure as an estimate of the number of 18,000-pound single axle loads expected to traverse a section of pavement during the pavement design life. Different axle arrangements could have a very different effect on the pavement even when the load is the same, as shown in Figure 14. An important use of ESALs for TxDOT is to help determine pavement thickness, along with factors like roadbed type and climate.

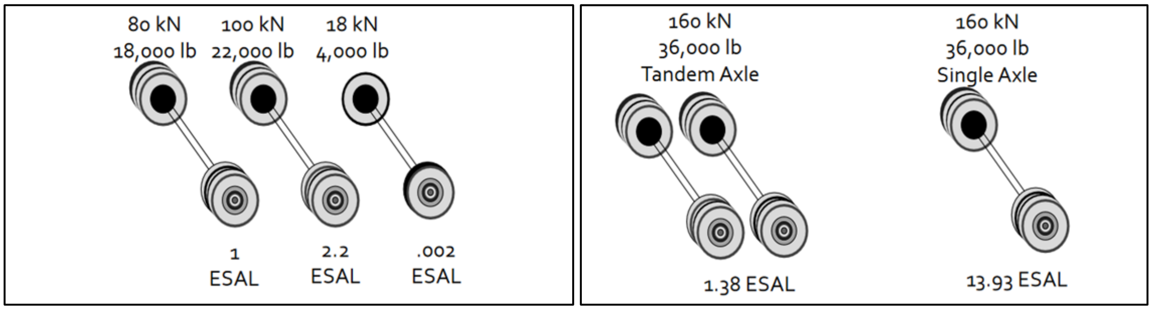

Figure 14: ESAL Comparison Single Axles and ESAL Effect for Different Axle Arrangements (Source: John Haddock)

HIGHWAY DESIGNATION

TxDOT allocates specific designations to highways located within Texas, depending on their construction standards, design requirements and specifications, funding sources, projected life and main purpose (TxDOT, 2017). These designations include Interstate Highway (IH), US Highway (US), US Highway Alternate (UA), State Highway (SH), State Highway Loops and Spurs (SL/SS), Off Interstate Business Route (BI), Off State Highway Business Route (BS), Off Farm or Ranch to Market Road Business Route (BF), Urban Road (UR), Ranch Road (RR), Farm to Market Road (FM), Ranch to Market Road (RM), Park Road (PR), Recreation Road (RE) and Principal Arterial State System (PA).

For the purpose of the analysis, four categories were defined: IH, US, SH and FM. The reason is that these are the most numerous and lengthier road designations, and as such most of the data collected refers to them. However, because there is also information regarding other designations, categories that shared similar functions were bundled together, such as FM and RM, SH and SL/SS, etc.

Primary routes include IH and US which form part of a system of expressways that go through more than one State (TxDOT, 2017). US were implemented before IH were. SH conform a network connecting internal, state maintained highways. They can belong to both primary and secondary routes. FM are roadways that connect rural or agricultural areas to market towns and are part of a system of secondary routes and are the most numerous – length and number – in Texas. The length of the state highway network is 90,000+ centerline miles, and around 200,000 lane miles. Figure 15 shows the general aspect of different TxDOT-maintained highways with their respective classification status.

Figure 15: Clockwise from Upper Right: IH-35, SH-55, US-287 and FM-1

Chapter 4: Methodology

The first part of this chapter describes the steps followed to compile the information used in this thesis. The information was extracted from TxDOT databases. The use of CSJ to locate projects in the TxDOT roadway network is described. The concept of Texas Reference Marker (TRM) is introduced. TxDOT uses TRM to link project information contained in different databases. Then the procedure followed for the Segmentation of TxDOT Control Sections is presented. The concept of Project Timeline, describing the effective life of the treatments considered in the study is introduced next, based on the PM individual performance curves. Finally, the PM treatments considered, the traffic information indicators included and the method to standardize the costs of the PM treatments to allow for direct comparison between them are explained.

In the second part, the simulation followed to assess the LCCA of PM treatments in Texas is presented. For this, the concepts of serviceability and of service life are introduced. Afterwards, the implemented LCCA is explained, step by step, along with the considerations and assumptions relevant for this work.

Database Development

This thesis sought to evaluate the LCCA of the most widely used PM treatments in Texas. Only chip seals, microsurfacing and thin overlays are considered. To compile the database used in this work, TxDOT-maintained databases were used. These were not limited to the ones containing information on contracted projects and include the DCIS and SM, and the PMIS – which stores data on both contracted and in-house projects, but also MMIS and Compass that contain information of in-house projects. DCIS contains information collected since 1994 and PMIS since 1984, while SM has been functioning since 2005.

This thesis information collected between 1994 and 2015 and TxDOT collected information was processed and merged. Automated process was implemented to do so, but manual checks were also involved. The main objective of processing TxDOT databases was to extract location, date, and design-related information for pavement sections with and without PM treatments applied (Serigos, 2016).

PROJECT LOCATION

The CSJ number was the key descriptor for the record of each project in TxDOT databases (TxDOT, 2006). All projects, if contained in a TxDOT database, are assigned a CSJ number, and can be linked through it. It is a nine-digit number consisting of four digits representing the control, two digits representing the section and a three-digit job number. If the control number is less than four digits, zeros are included before this number.

- Control – A definite section of highway with well-defined geographic termini – usually 25 to 30 miles (TxDOT, 2006).
- Section – Part of the control that is a shorter, logical, and practical length – usually 0.5 miles or less (TxDOT, 2006).
- Job – The unique job number assigned in numerical order within the limits of each control-section.

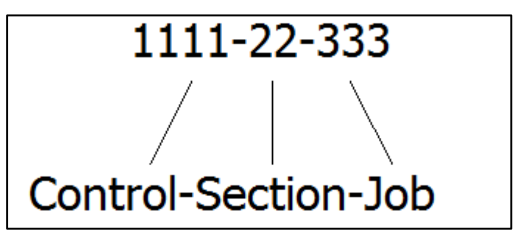

Figure 16: Example of CSJ Number (Based on: TxDOT, 2006)

In practice, the first six digits reflect the control section (ConSec) in which the M&R procedure was applied (Serigos, 2016). As described before, each of these numbers represents a unique pavement segment within TxDOT-maintained roadways. Employing the TxDOT Statewide Planning Map App, ConSecs can be visualized in colored lines. For example, Figure 17 shows the Austin area. ConSec 0113-12 in bright green is located in Texas State Highway Loop 343, between SH-343 and IH-35 – in downtown Austin – and has a length of 1.348 miles.

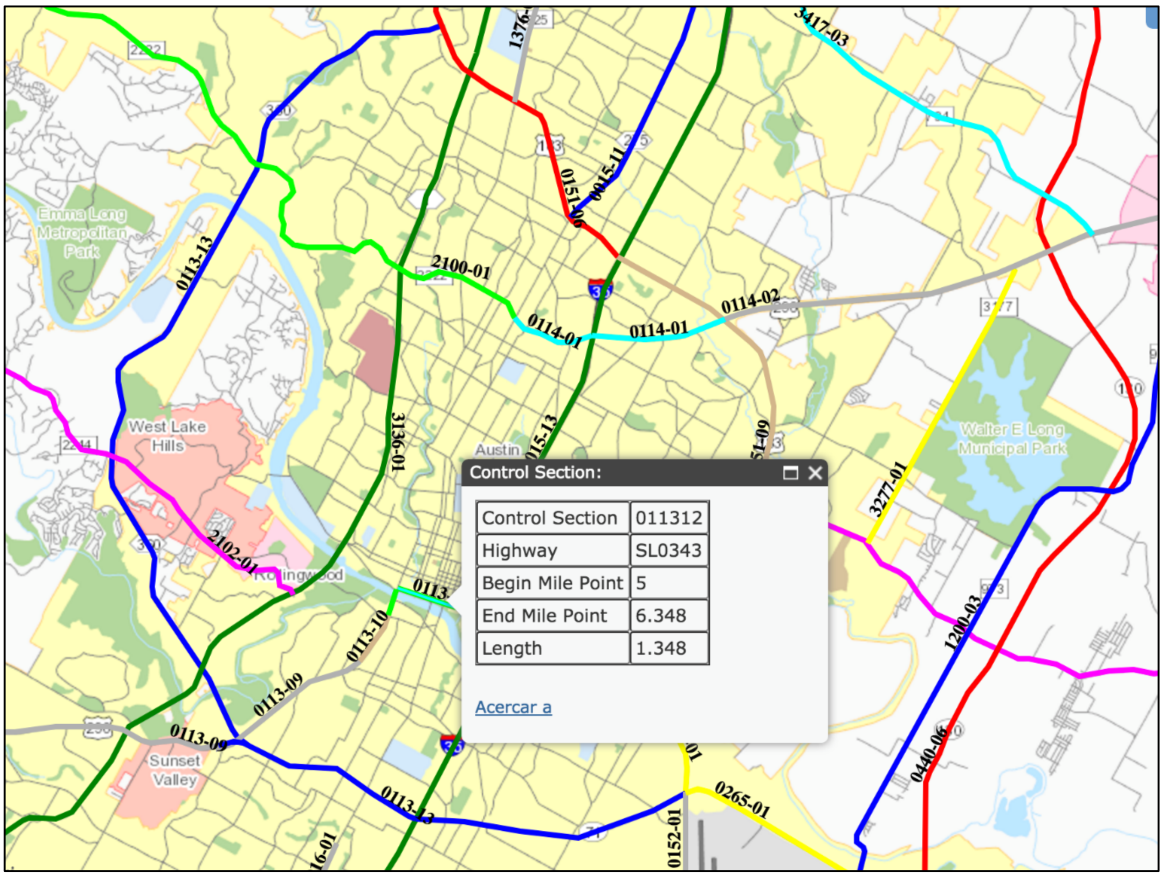

Figure 17: CSJs in the Austin Area (Via: TxDOT Statewide Planning Map App)

In most cases, the PM treatment is not applied on all the ConSec (Serigos, 2016). Through application would not be cost-effective and only pavement sections in need of PM are going to be treated. Considering this, the location of each contracted work was defined by the ConSec and by including the beginning and ending point of the applied treatment – located within the ConSec. The location of both the beginning and ending points for a given CSJ could be presented in two formats: in TxDOT´s descriptive language and in TRM.

- TxDOT´s descriptive language – A non-numeric format to delimit the zone in which M&R was applied. For example, project CSJ 0188-05-032 in Brazoria County is a chip seal treatment that starts in "Texas Street" and finishes "0.25 miles south of County Road 310".
- Texas Reference Marker – Numeric format defined by the distance to a highway TRM (Serigos, 2016). The TxDOT Statewide Planning Map App can be used to visualize TRMs. For example, in Figure 18 TRM 235 – located in IH-35 near downtown Austin – is observed. From this, TRM "235+0.17" would indicate that the limiting point of the job is located 0.17 miles after TRM 235 on the highway direction of travel.

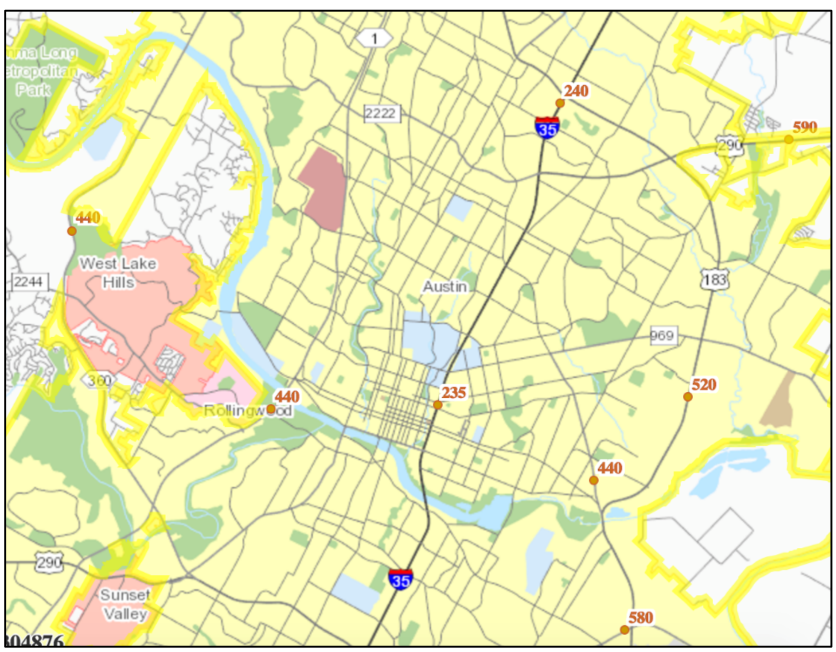

Figure 18: TRMs in the Austin Area (Via: TxDOT Statewide Planning Map App)

In the cases when the information on the location of the CSJ was presented in TxDOT´s descriptive language, manual data processing was required. Manual processing was not practical due the size of the databases – more than 14,000 PM treatments in this case. As a consequence, the database – developed at UT Austin – included mostly ConSec that had their CSJs referenced to a TRM. Manual work based on TxDOT´s descriptive language was undertaken with the objective of increasing the number of projects and to make the analysis more robust.

To do the manual measurement of the length of the ConSec based on TxDOT´s descriptive language, Texas Preservation´s TRM (TPTRM) was employed. First, the descriptive boundaries for the ConSec were obtained from the databases. Then, the location of the specific project was found on a map. TPTRM allows locating highway sections in Texas by providing district, county, highway or address. Afterwards, TPTRM measurement tool was used. Figure 19 shows road TX-73E located in Winnie, Chambers County, along with the bookmarks (green flags) used to measure project length and location.

Figure 19: Manual CSJ Length Measurement (Via: Texas Preservation TRM)

PM treatments are implemented only in the pavement segments that require them, not on uniform segments. The location of a CSJ is not uniform and might overlap – at least at some point – with other CSJs applied at different points in time (Serigos, 2016). This results in most pavement segments through TxDOT´s highway network having different M&R records. Serigos (2016) illustrated the situation (Figure 20). The horizontal black lines show the location limits of three CSJs applied within the same ConSec in three different years: 1998, 2006, and 2012. The overlapping segments of these three PM treatments yields five different portions of road that have had a different number of treatments applied. For example, between 216+0.10 and 218-0.18 three treatments were applied, while between segment 248+0.74 and 248.081 only two such treatments were carried out. By implementing this criterion to segment all ConSec, pavement segments with homogeneous PM history was obtained.

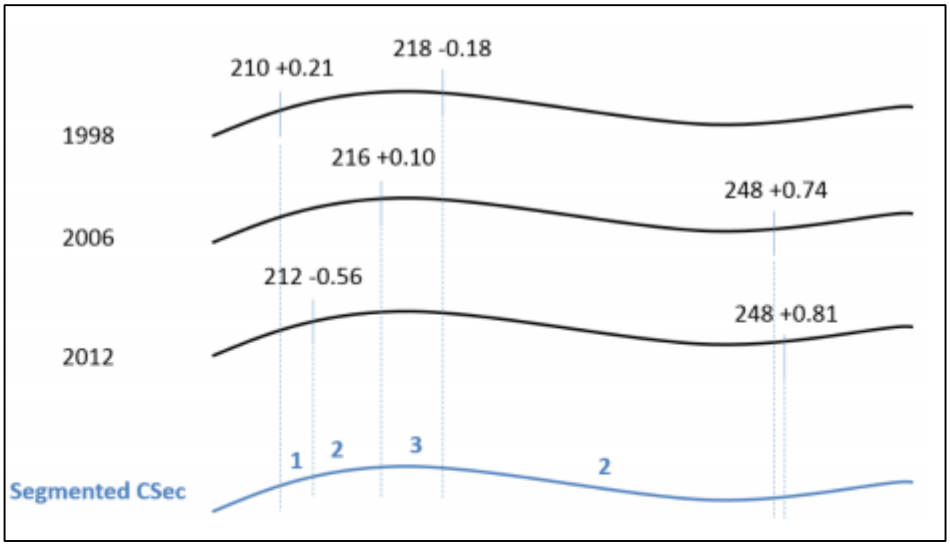

Figure 20: Segmentation of TxDOT Control Sections (Source: Serigos, 2016)

The compiled database included all 14,000+ CSJs of PM treatments applied between 1994 and 2015, along with the project length (miles).

PROJECT TIMELINE

The effective life of a PM treatment started being measured at the date in which the surface it was applied to was opened to traffic (Serigos, 2016). The ending date for each CSJ was extracted from TxDOT databases. In the same way, the ending time of the PM effective life – in the cases when it was observed – was defined as the date when the next treatment was applied to the same pavement surface section.

Once the dates of start and end for each CSJ were extracted for PM contracted projects, ending times were checked and corrected, if necessary, based on data from TxDOT internal works. To achieve this, PM information from the MMIS database was used to verify whether in-house projects were performed during the effective life of the treatment for each section and, if so, correct the ending date of the respective CSJ as the earliest in-house PM treatment applied during the treatment's effective life (Serigos, 2016). Contracted and in-house projects were complementary.

As double-check of the start and end date for PMs applied to each pavement surface, the dates extracted from the processed databases were verified to correspond to the expected improvement in the pavement condition. To achieve this, the performance curve of each pavement section included in the database was visually inspected (Serigos, 2016). When the processed dates were within two years apart from the observed improvement in the pavement condition, the date was corrected. Serigos (2016) shows this employing Figure 21, which shows the mean and most critical CS, DS and IRI values throughout time for a project located in the main lane of US-70 at the ConSec 0145-06, located in Floyd County between miles 320 and 337.98.

The figure shows two PM treatments were applied: a chip seal in late 2007 and another chip seal four year later. Major rehabilitation was then applied in early 2014. The performance curve shows that before the major rehabilitation was applied in 2014, the pavement condition improved. Therefore, the application date for this PM treatment estimated in the previous step was corrected to match the dates on which the pavement condition score increased. The data used to perform the LCCA was manually assessed to ensure the highest possible quality.

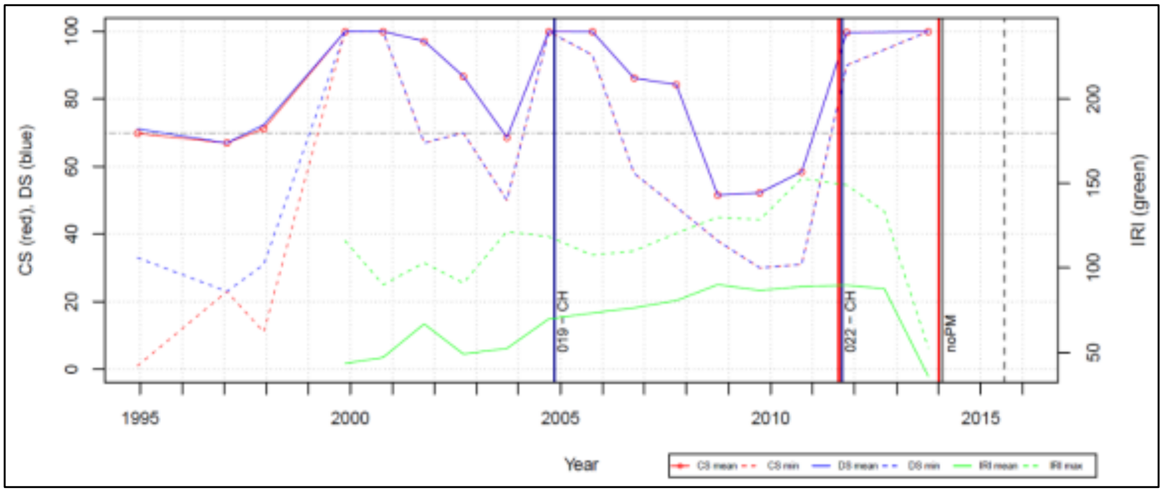

Figure 21: PM Individual Performance Curves before Manual Inspection based on Application and Replacement Dates (Source: Serigos, 2016)

The above describes the procedure to obtain the effective life of PM treatment for which there was information on the end date. As mentioned before, the study included both observed information – when the PM treatment has completed its effective life – and censored information. The latter was used when the PM treatments were still in service and their ending time had to be estimated rather than observed.

The PM treatment time of application was extracted along with the time of replacement. Censored information was signaled with a one, while non-censored (observed) was indicated with a zero.

TREATMENT TYPE, TRAFFIC INFORMATION AND PROJECT COST

TxDOT databases contain information on all the maintenance activities that are conducted on its roadways. These include PM treatments and major rehabilitation projects. However, they also include works like the installation of safety lighting, landscaping, mowing and thermoplastic striping. Only PM treatments were selected and linked to the final database.

The PMIS database contains traffic information regarding roads in Texas. The selected indicators for this study were AADT and ESAL. The type of highway was also included in the study, grouped as follows:

- IH – IH
- US – US, UA
- SH – SH, SL/SS, BI, BS
- FM – FM, BF, UR, RR, RM, PR, RE, PA

The database contained also the total, final cost paid to the contractor. During the bidding process, the lowest bid is generally granted the contract. TxDOT allows the contractor to have a final cost within a five percent difference with the bid. This final cost englobes all activities performed during the application of the PM treatment, as well as the cost of materials, equipment and workforce. Although materials usually account for the majority of the final cost, it was decided to include all items as this would yield more realistic results, and be the base for future sensitivity analyses.

With the cost of the materials for the PM treatments, their length, and the number of lanes – also given in the databases – the total cost per mile was obtained. This was calculated by dividing the total cost of the project by its length (in miles) and then by the number of lanes in the section. This was needed in order to have a standard unit of measurement, and to be able to draw direct comparisons between PM treatments. Once this information was collected and edited, the simulation was run.

Simulation

With the compiled information, a stochastic approach to calculate the life-cycle cost analysis of included PM treatments was implemented. This was done through MCS, using MATLAB. As mentioned before, a stochastic approach was preferred over a deterministic one because it allowed to account for uncertainty in the input parameters and also, for the measurement of the variability of the LCCA outputs, which could be used for reliability analyses later on.

The analysis period was set to 25 years, as it was reasonable to assume that if the treatments were applied correctly, no major rehabilitation would be required before the end of this period was reached. In the same way, it was assumed all of the PM treatments were applied for the first time in the year 2016, on a pavement section that was still in a good condition. This assumption could be eliminated in future experiments, but it is out of the scope of this work. The independent parameters selected for the LCCA were project cost and time.

It was further assumed that once a type of PM treatment was applied, successive applications at the end of its effective life would be of the same type. This assumption was for practical reasons, given that in practice it depends on both experience and engineering judgement, which leads to heterogeneous selection across the different Texas districts.

PROJECT COST

Project cost is represented by the total cost per lane mile of the applied PM treatment. As stated previously, a lognormal distribution was used to simulate the costs. To obtain the inputs required by this distribution, the historical costs of the PMs implemented during the 20 years were obtained from TxDOT databases. However, raw costs cannot be used as inputs because the value of money over time is not steady. For example, if a PM treatment was applied in 1994 and had a cost of $20,000 and another was applied in 2005 and also costed $20,000, in reality the first one was more expensive.

For this, all costs were transformed to their 2016 value using the rates suggested by the Bureau of Labor Statistics. A discount rate was applied to the individual costs depending on the year they were placed. This allowed transforming the costs to present equivalent total cost, and having the possibility to compare them directly. The year they were placed was chosen as the reference for the cost because it was assumed it was the same year they were paid for – no future paying was allowed.

SERVICE LIFE

Time was represented by the effective life of the applied PM treatment. A Weibull distribution was used to simulate the effective life of the treatments – the time between two consecutive treatment applications. To obtain the input of this distribution, a manual analysis was implemented with the information collected over a 20-year period by TxDOT. The reason a manual analysis was required is because the treatments applied during the 20 years overlap, but their effective life is not always the same.

Non-censored information allowed to extract the effective life of a given PM treatment as it contained both the date of application and replacement. Censored information required the effective life be estimated using survival analysis, as the only information reported was the application date. This was because the databases used for this work included projects that were still in service and thus the end of their effective life had not yet been reached.

LIFE-CYCLE COST ANALYSIS PROCEDURE

Once the information was collected and formatted, the variables to calculate the LCCA selected, the distributions to represent them estimated, and the simulation method developed, it was possible to proceed with the experiment. The experiment involved the following milestones:

- The analysis started by assuming the first PM treatment was always implemented in the same year (2017). So first, the simulation of the cost per lane mile of implementing a PM treatment was carried out, using a lognormal distribution.
- The time of the application of the subsequent treatment was determined based on the simulated effective life of the treatment. For this, the effective life of the treatment applied in 2017 was simulated, using a Weibull distribution. Recall that a PM treatment was applied when the pavement structure was still in a good condition.
- Once the effective life – in years – was estimated, another simulation of the cost was carried out for this PM treatment application. Both the effective life and cost of the treatments were considered to be independent.

These steps were repeated until the 25-year analysis period was evaluated. The number of times a PM treatment was applied depended on the length of the simulated effective life for the treatments obtained during the analysis. For example, if the simulated lives were six, eight, four, five and seven, the number of PM treatments applied would be six, if we consider that a treatment was applied at the beginning of the simulation. It is important to note that the effective life is a continuous variable. If the treatment was applied six times, it also means that there were six simulated costs associated with it.

The total cost per lane of applying a treatment to a given pavement segment was then computed as the sum of the discounted costs for all the PM treatments that were applied during the analysis period minus the salvage value, at the end of the 25-year period. The salvage value was defined as the estimated monetary value a pavement section would have upon the end of its service life. Therefore, the salvage value was calculated as the cost of the last PM in the section times the percentage of the remaining life of that treatment. An important assumption was that once a PM treatment has been implemented in a given section, the same type of treatment was going to be applied throughout time, as in common practice (Wimsatt et al., 2005). In addition, a four percent interest rate was used in the analysis as suggested in the literature for estimating the NPV for highway projects in Texas (Wimsatt, 2005).

The Monte Carlo Simulation was implemented in Matlab. The simulation included 100,000 outcomes for each one of the studied scenarios. Within the simulation, for every outcome, the effective life of each PM treatment, along with the associated costs per lane mile were independent until the 25-year analysis window was completed. A sketch representing the process can be seen in Figure 22.

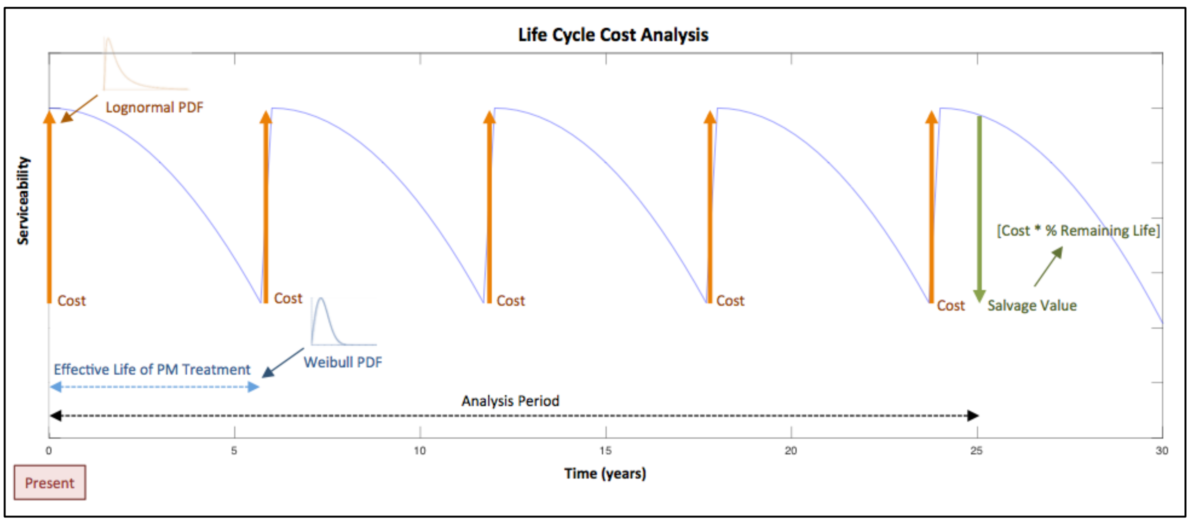

Figure 22: Life-Cycle Cost Analysis Procedure

Chapter 5: Life-Cycle Cost Analysis Results

Once the information relevant for this study was extracted from TxDOT databases and information systems, following the procedures described in Chapter 4, and compiled together into a single database, it was possible to proceed with the analyses. The effects of the facility type, traffic volume and traffic loads were studied, seeking to understand what conditions affect the most the life-cycle of PM treatments in Texas.

Effective Life

The distribution of the effective life of the analyzed PM treatments can observed in Figure 23. Chip seals (in green) had a larger median effective life than the other treatments. Thin overlay, in blue, appeared to have an effective life that was similar to that of the microsurfacing (in red).

Even though chip seals presented a mode slightly higher, the three treatments had similar distributions. In the figure, it can be appreciated that the mode of the effective life for microsurfacing and thin overlays was of approximately two years, while that of chip seals stood at approximately three years. In all three cases the distribution was skewed to the right.

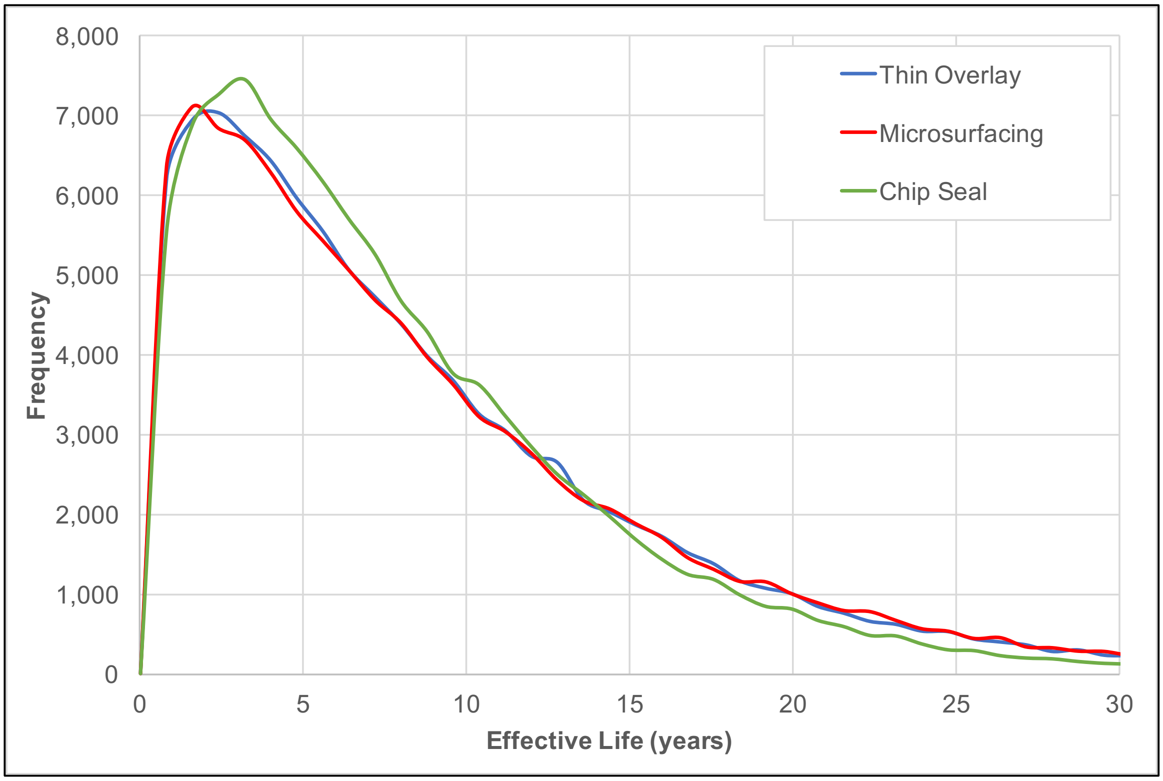

Figure 23: Effective Life of PM Treatments

Cost per Lane Mile

The cost of the PM treatments included mobilization, materials, and construction. In Figure 24, it can be observed that chip seals and microsurfacing – in green and red, respectively – had lower costs and variability as compared to thin overlays – in blue. Thin overlays costs were more spread out. Thin overlays are relatively new so the industry and the agency are going through the learning curve.

Chip seals showed a median cost of less than $15,000 per lane mile, rarely exceeding $40,000. Microsurfacing had a median cost of around $24,000 per lane mile and usually lower than $60,000. Finally, the cost distribution for thin overlays showed a median cost per lane mile of $59,000, commonly larger than $40,000 and as high as more than $160,000.

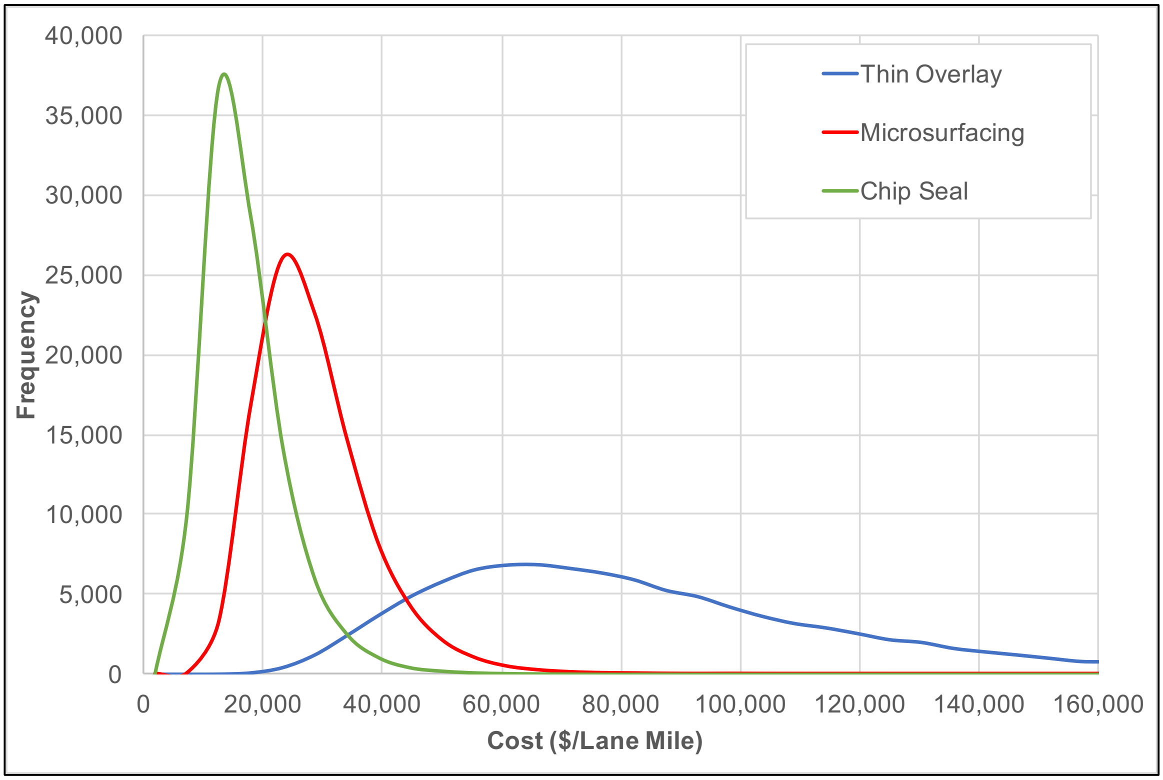

Figure 24: Cost per Lane Mile of PM Treatments

Life-Cycle Cost

Figure 25 shows the life-cycle cost of the three treatments evaluated. It can be seen that chip seals, in green, were the most cost-effective, with relatively small variability and an expected median cost of $84,000 per lane mile during a 25-year period. Microsurfacing, in red, showed more variability than chip seals, but also showed a median life-cycle cost of $87,000 per lane mile – which was similar than that of chip seals. Finally, thin overlays, in blue, presented a more spread out LCC distribution, making it less predictable than the other cases. Although its median cost was $120,000 per lane mile (50 percent larger than the other PM treatment options) it presented a long tail and in many cases surpasses the $200,000 barrier.

It is important to notice that because the distributions for the effective life of the treatments were fairly similar, the cost seems to exert a large influence in the LCC of the PM treatments evaluated.

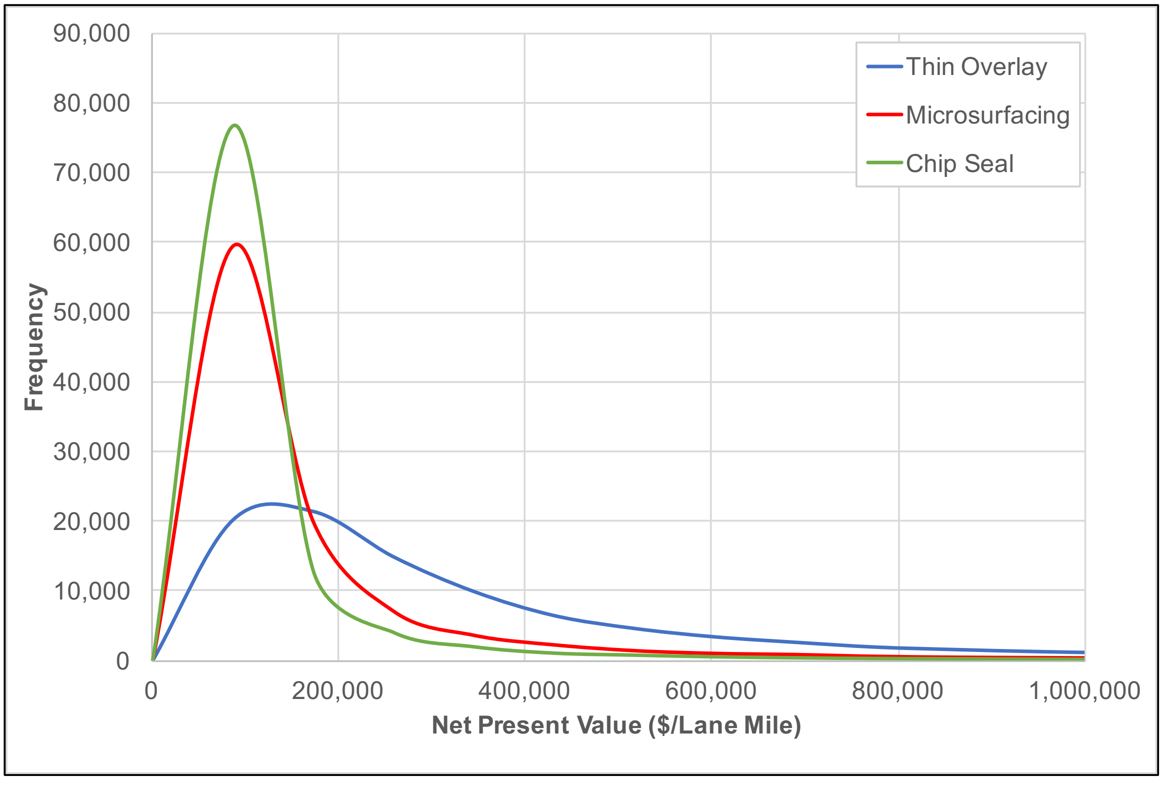

Figure 25: Life-Cycle Cost of PM Treatments

Effects of External Factors on the LCCA of PM Treatments

Once the results of the LCCA were obtained, it was considered important to understand what are the critical that influence them. To achieve this, separate LCC analyses were run for three factors, seeking to gauge their effect and how the selection of the treatments could be optimized. The three factors taken into consideration for this thesis were the facility type, traffic volume (AADT), and traffic loads (ESALs).

EFFECT OF FACILITY TYPE

In this study, roads were included in one of four categories: Interstate Highways (IH), US Highways (US), State Highways (SH) and Farm-to-Market Highways (FM). Although there are many other classes, they were aggregated into the four groups shown in Figure 26.

Chip seals, in green, showed the most cost-effective alternative for all facilities, and thin overlays, in blue the most expensive. Microsurfacing, in red, presented the mid-way alternative but closer to chip seals. For FM, chip seals presented the lowest LCC, almost half of that for microsurfacing. One possibility is that TxDOT in-house projects are more cost-effective. TxDOT in-house projects are usually smaller than contracted ones, and so are less costly and employ the traditional chip seal treatment.

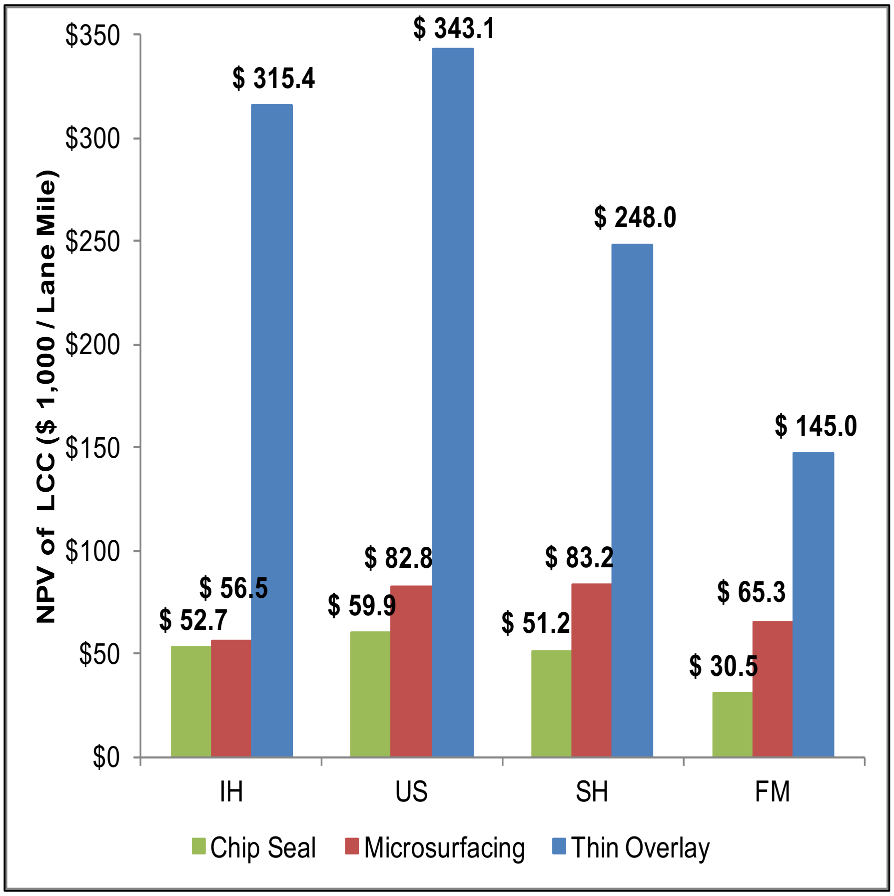

Figure 26: Effect of Facility Type

EFFECT OF TRAFFIC VOLUME

Traffic volume expressed as AADT, represents how busy a roadway is, and it is an important factor affecting the performance of a given treatment. For example, if two similar PM treatments are applied at the same time to two surfaces that currently present the same condition, the one with the more traffic volume will deteriorate faster.

In Figure 27, it can be observed that chip seals, in green, were the most cost-effective alternative for all traffic levels. Thin overlays, in blue, were still the most expensive option, and microsurfacing, in red, were again the mid-option.

However, it was interesting to see that as traffic increased, the gap between chip seal and microsurfacing decreased. That is, for low traffic, chip seals was the best option but as traffic volume increases, microsurfacing could become a good alternative. Thin overlays did not show a clear tendency, and its use should be considered in a case-by-case basis.

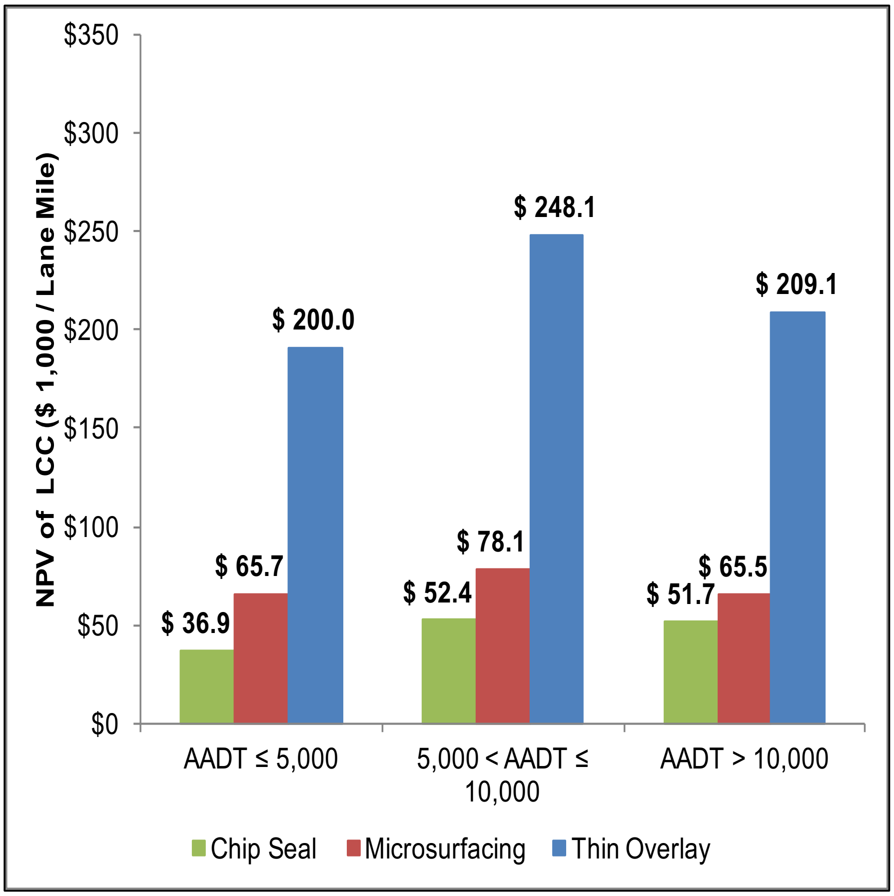

Figure 27: Effect of Traffic Volume

EFFECT OF TRAFFIC LOADS

Traffic loads, represented by ESALs, provide an idea of the type of traffic circulating through a given road. This is important because the heavier traffic loads, the faster the pavement will deteriorate.

Figure 28 shows that seal coats (in green) were the most cost-effective alternative in all cases, followed by microsurfacing (in red), and thin overlays, in blue. All costs increased as the number of ESALs increases but, as the loads increase, the LCC of microsurfacing became similar to the one of chip seals. This could be interpreted as chip seals being good for roads with light traffic, but becoming less efficient as the ESALs increase.

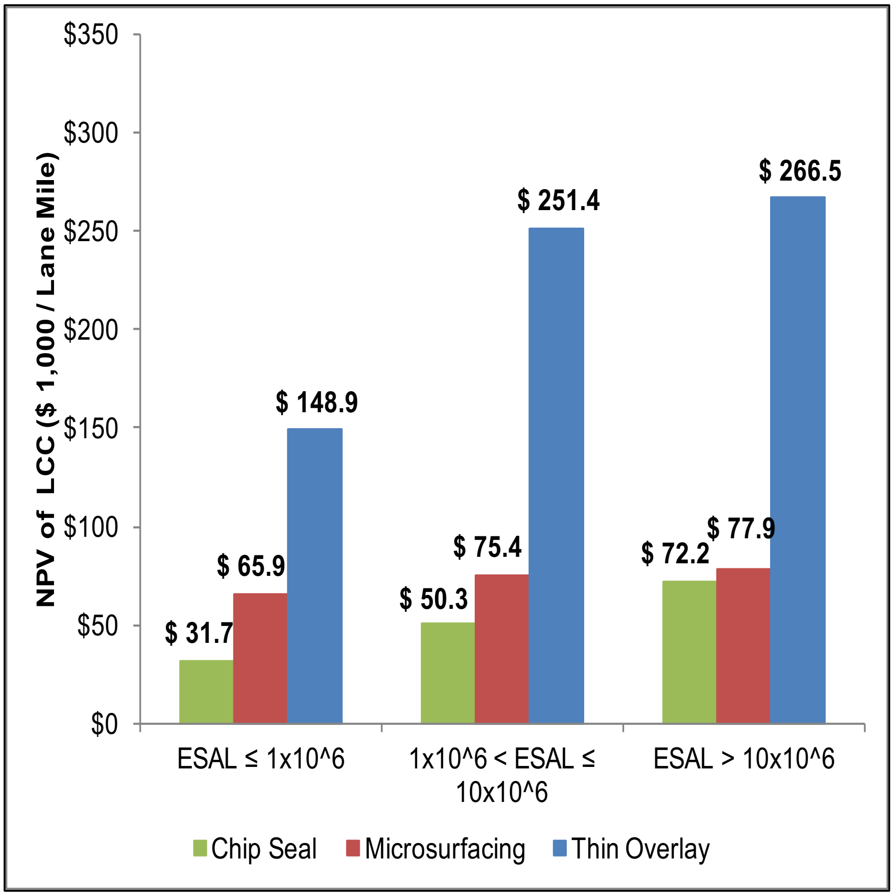

Figure 28: Effect of Traffic Loads

Chapter 6: Conclusions and Recommendations

The timely application of preventive maintenance (PM) treatments has proved a cost-effective way to maintain paved roads. This work sought to contribute to the literature by developing a probabilistic LCCA that allowed for the evaluation and comparison of the three treatments most commonly used in Texas: chip seals, microsurfacing and thin overlays. The novelty of the study being that it was based on actual data, provided by TxDOT, and comprising 14,000+ projects over a 25-year analysis window.

Maintenance and rehabilitation techniques can be divided into three main stages: routine maintenance, preventive maintenance and major rehabilitation. Previous studies found PM to be cost-effective, as their implementation decreased the rate of pavement deterioration. These treatments are also used to maintain an acceptable surface friction on the pavement and prevent water from infiltrating through the pavement and reaching the subgrade. PM treatments need to be applied while the roadway is still in a good condition, shows only minimal distresses and is structurally sound.

The Texas Transportation Commission has set as a goal that 90 percent of the Texas highway network has to be rated "Good" or better at any given point in time. To measure the condition, TxDOT uses the Condition Score (CS). Further, TxDOT has created a Four-Year Plan, which seeks to evaluate its highway network holistically to optimize spending and maximize benefit. TxDOT has traditionally employed one of three main treatments: chip seals (or seal coats), microsurfacing and thin overlays.

TxDOT has an array of pavement-related information stored in different databases. These data are kept separated for in-house projects and contracted ones. This was because most PM treatment projects are contracted and the collection of information is generally more accurate. The concept of effective life was used in this thesis. Effective life was defined as the time that elapses between two consecutive treatment applications.

Conclusions

The most important aspect of this research effort was that it was based on actual data, provided by TxDOT. Further, a procedure was described to use TxDOT databases and information systems and extract information relevant for this study.

All three treatments evaluated showed similar effective life distributions, and their median values were similar: two years for microsurfacing and thin overlays and three years for chip seals. The cost chip seals and microsurfacing presented lower variability compared to that of thin overlays. Chip seals had a median cost of $14,500 per lane mile, and microsurfacing of $24,000. Thin ovelrays median cost was $59,000 per lane mile, making it more than four times more expensive than chip seals and two times more than microsurfacing. Although there was variability, most chip seals cost was less than $40,000 per lane mile and most microsurfacing less than $60,000. To date, the cost of thin overlays is highly variable. One reason to explain this is that chip seals and microsurfacing have been in use for a longer time than thin overlays, and so their techniques have been mastered, while there is a lot of room to improve the procedure for thin overlays.

Looking at the LCCA, chip seals were the most-cost effective alternative, with a median of $84,000 per lane mile during the 25-year analysis window. Microsurfacing presented a LCC just $3,000 larger than chip seals. For thin overlays the median LCC was $120,000 per lane mile, but the large variability made it hard to predict. Due the distribution of the effective life for the three PM treatments being alike, the LCC were influenced largely by the cost of the treatments.

Considering external factors on the performance of PM treatments, chip seals were the most cost effective for the four types of facilities considered (IH, US, SH and FM), followed by microsurfacing and thin overlays, respectively. However, the cost for chip seals was consistent for IH, US and SH, and lower for FM. Thin overlays presented the largest costs in all cases. For IH, chip seals and microsurfacing presented similar costs. This is interesting since chip seals are not usually placed on IH. On the other hand, for FM roads, where chip seals are usually placed, their cost was almost half than that of microsurfacing.

Regarding traffic volumes, chip seals also showed the lowest LCC for all volumes, followed by microsurfacing and thin overlays, in that order. It is important to note that as traffic increased the gap between the LCC of chip seals and thin overlays reduced. This would make low-volume roads not appropriate for microsurfacing, but better suited for high volume roads.

As for traffic loads (in terms of ESALs), chip seals were again the most cost-effective, and thin overlays the least cost-effective. The LCC of chip seals showed linear increase with the loads, and microsurfacing an almost uniform LCC, notwithstanding the increase or decrease of the loads. This could mean that chip seals are good for roads experimenting low loads, decreasing their efficiency as loads increase. Microsurfacing seems to be desirable only in cases where medium to large loads are expected.

Finally, chip seals emerged as the most cost-effect PM treatment, even in environments where they are not the traditional alternative of choice, like IH. Microsurfacing proved an excellent alternative to chip seals as traffic volumes and loads increase. Thin overlays are to be evaluated in a case-by-case basis as they had the less predictable behavior. They could work well in pavement sections located in intersections, turning points and stop signs, where higher stresses are involved.

Recommendations

This study included pavements that were in "Good" condition, and structurally sound. The analyses targeted PM treatments used in Texas that were applied to flexible pavements. Expanding the work to include pavements in any condition and structural state and other pavement types would allow to study every pavement structure in Texas, and to obtain more generalized results.

Little information is available regarding the method different TxDOT districts follow to apply a given PM treatment. Research focusing on this may help understanding the sequence PM treatments are applied in, and the relationship between them.

Finally, taking into consideration the effect of environmental conditions (e.g. temperature, precipitation, subgrade type) could enhance the understanding of the LCC of PM treatments in Texas.

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